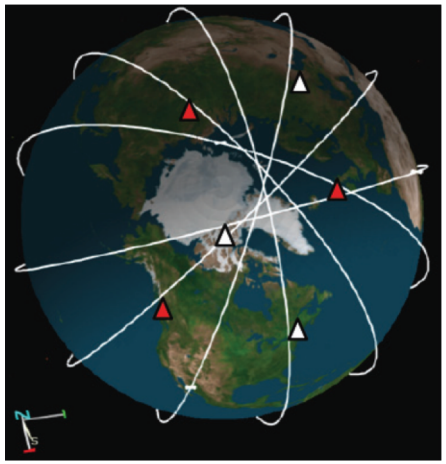
An Overview of the "Notional" Geospace Dynamics Constellation (GDC) Mission

A Strategic Mission Recommended by the National Research Council Heliophysics Decadal Survey as the next major Living With a Star (LWS) Initiative



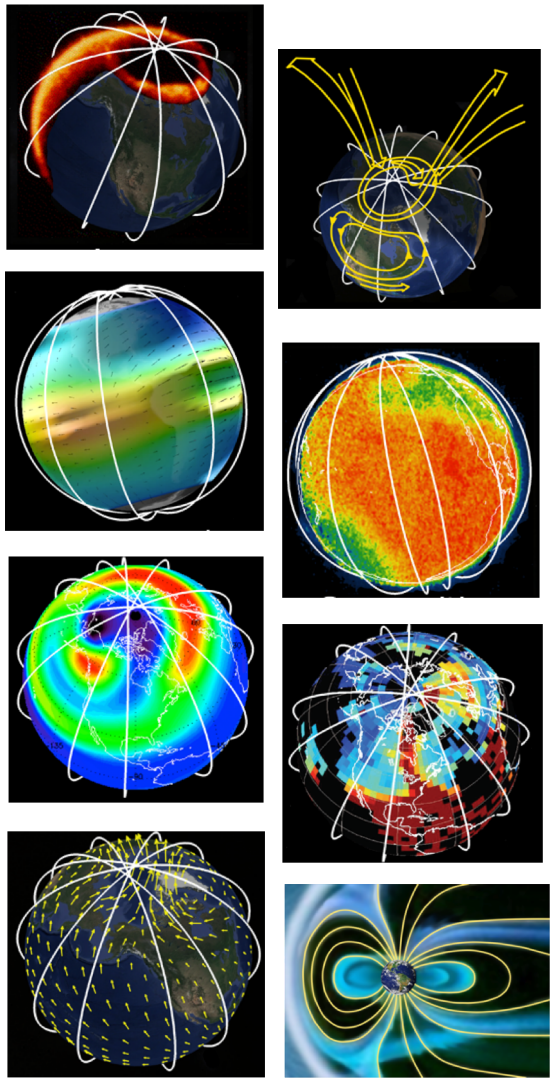
Rob Pfaff
NASA/Goddard Space Flight Center

May 15, 2018

Geospace Dynamics Constellation (GDC)

Overarching Goal

Understand how the ionosphere-thermosphere behaves as a system, connecting to the solar wind and magnetosphere above and the troposphere below.



GDC addresses

→ **Major Physical Processes/Questions**

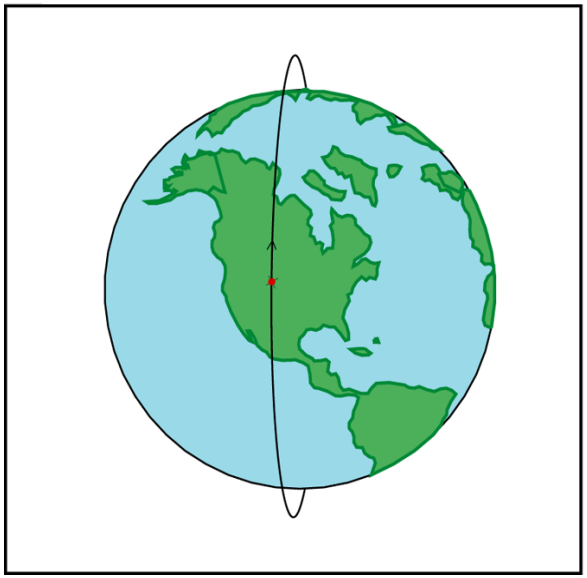
→ **Critical I/T Space Weather Problems**

→ **Input for "data-starved" models**

Geospace Dynamics Constellation -- Concept

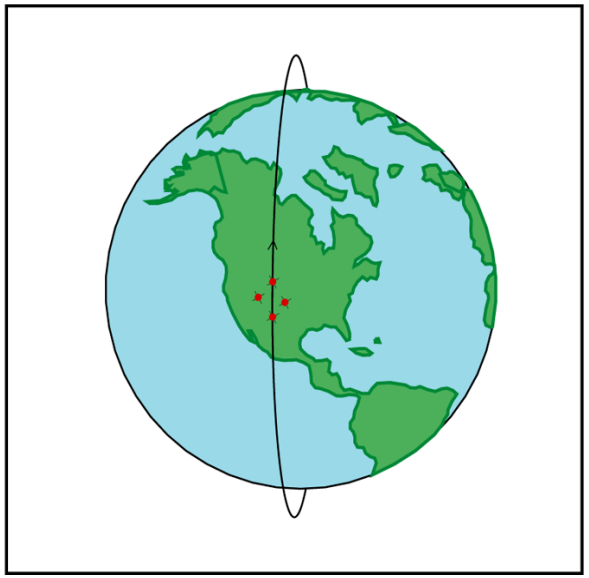
(Slide from LWS Ionosphere Mappers, ~2000)

Single Satellite



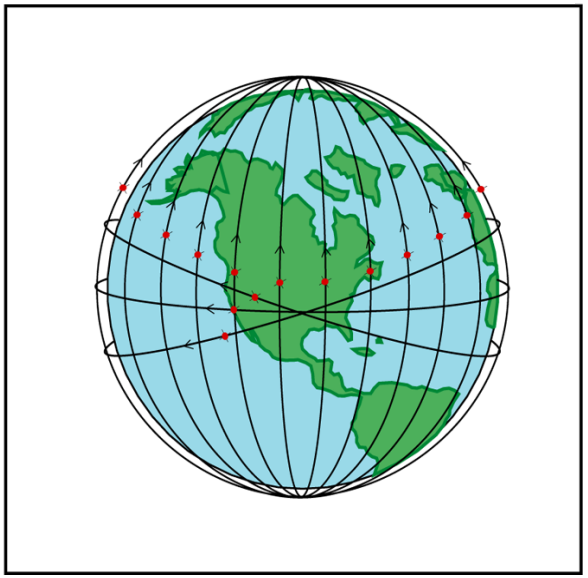
- Event Studies, Exploration
- Provide **Average** Global Conditions
- Example: **Dynamics Explorer-2**

Cluster of Satellites



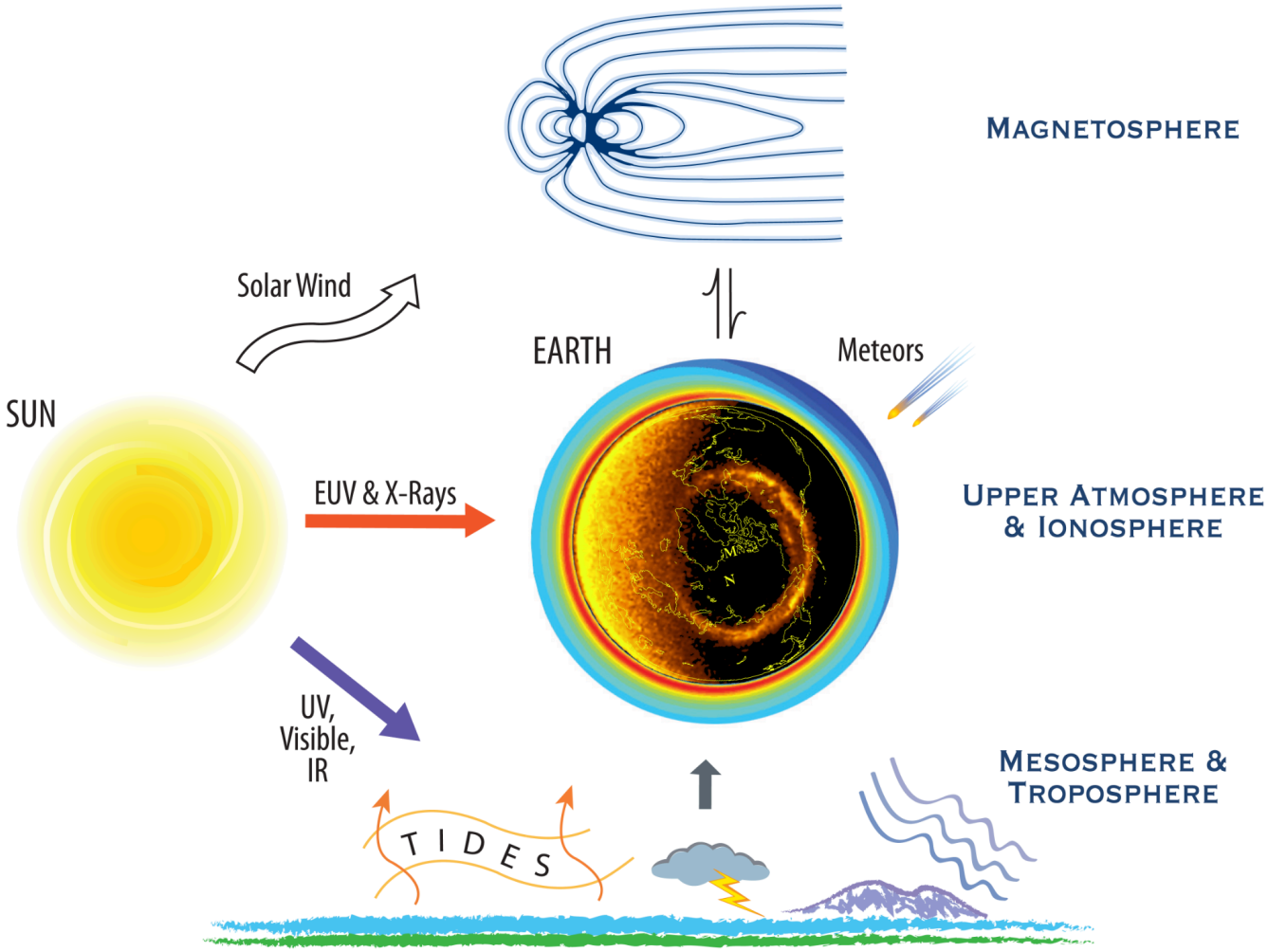
- Event studies resolved in Space,Time
- Reveal cross-scale coupling within ion, neutral gases
- Example: **Global Electrodynamics Connections**

Global Network of Satellites



- Global, simultaneous observations at all latitudes, local times
- Uncovers global-scale processes, coupling to other regions
- Reveals structure, large-scale waves along each path
- Example: **Ionosphere Mappers (GDC)**

Pathways of solar energy to the Upper Atmosphere and Ionosphere



GDC Scientific and Space Weather Motivation

→ GDC has a broad set of science objectives in keeping with its role as a strategic NASA Living With a Star mission.

→ GDC's strong scientific motivation addresses major ionosphere/thermosphere "unknowns" critical to our understanding

→ GDC's measurements of comprehensive plasma and neutral state variables and their external drivers on multiple platforms will significantly advance our comprehension of not only how the earth's upper atmosphere works but also how the upper atmospheres of other planets work as well

→ Appropriate for an LWS mission, GDC squarely addresses important space weather problems

Geospace Dynamics Constellation -- Science Objectives

Overarching Goal

Understand how the ionosphere-thermosphere behaves as a system, connecting to the solar wind/magnetosphere above and the troposphere below.

GDC Focus -- Critical Science Questions (from Decadal Survey)

1. How does solar wind/magnetospheric energy energize the ionosphere and thermosphere?
2. How does the IT system respond and ultimately modify how the magnetosphere transmits solar wind energy to Earth?
3. How is solar wind energy partitioned into dynamical and chemical effects in the IT system, and what temporal and spatial scales of interaction determine this partitioning?
4. How are these effects modified by the dynamical and energetic variability of the ionosphere-upper atmosphere introduced by atmospheric wave forcing from below?

IT coupling and response to Solar Wind Magnetosphere

IT global response to Magnetic Storms

IT response to forcing from below

These Objectives are Now Discussed within 4 GDC Focus Areas

GDC Focus Areas/Science Objectives

→ **Solar wind/Magnetosphere Forcing of the high latitude I/T system with feedback**

→ **Global Response of the ITM System to Geomagnetic Storms**

→ **Causes of Large Scale Structuring of the Ionosphere and Upper Atmosphere**

→ **Effects of Forcing from Below**

GDC Focus Areas/Science Objectives

→ **Solar wind/Magnetosphere Forcing of the high latitude I/T system with feedback**

→ Global Response of the ITM System to Geomagnetic Storms

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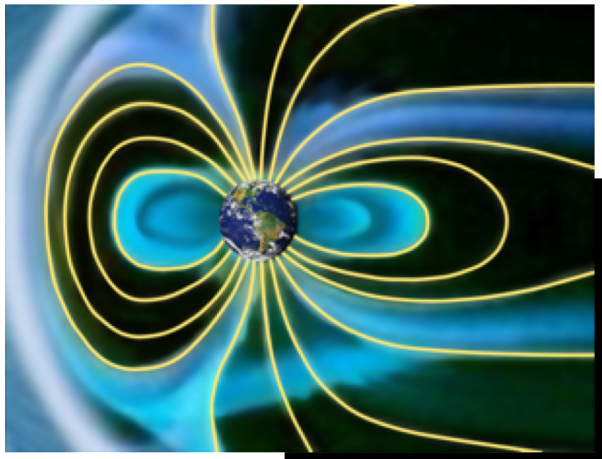
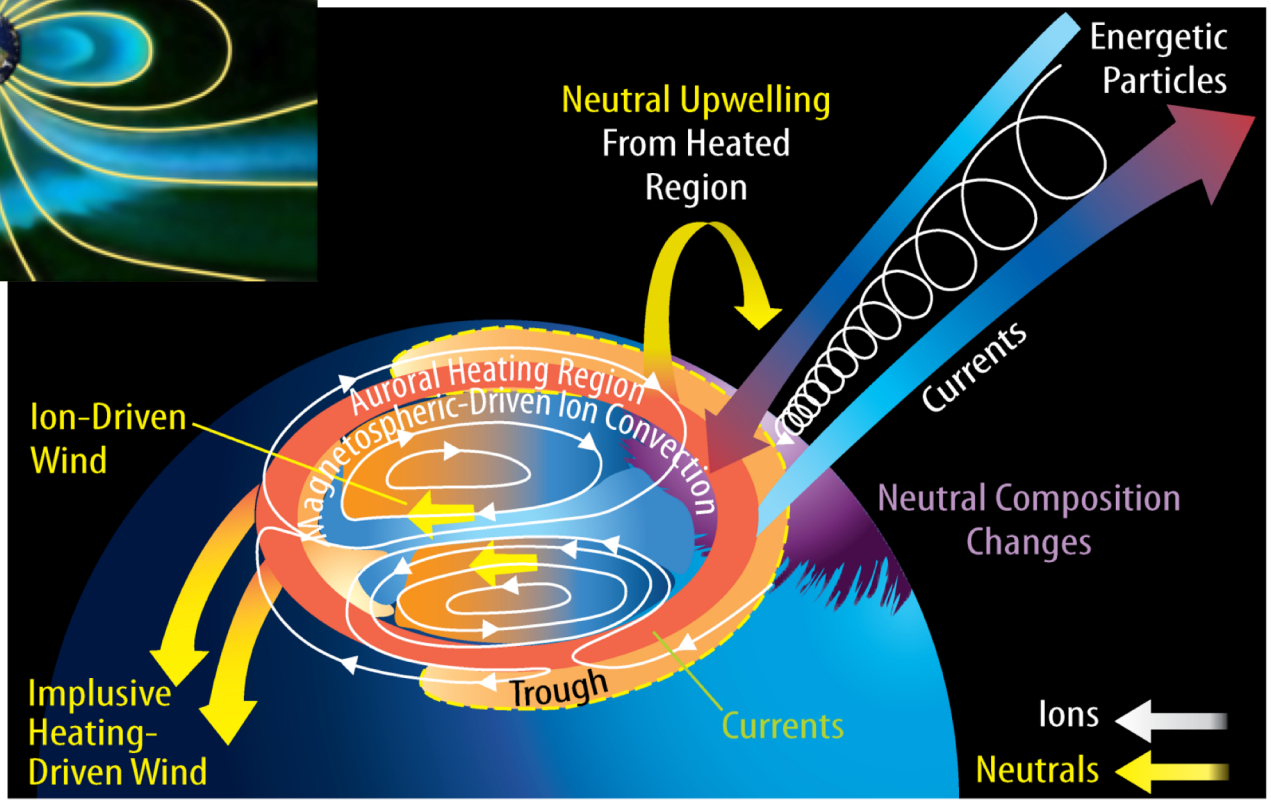
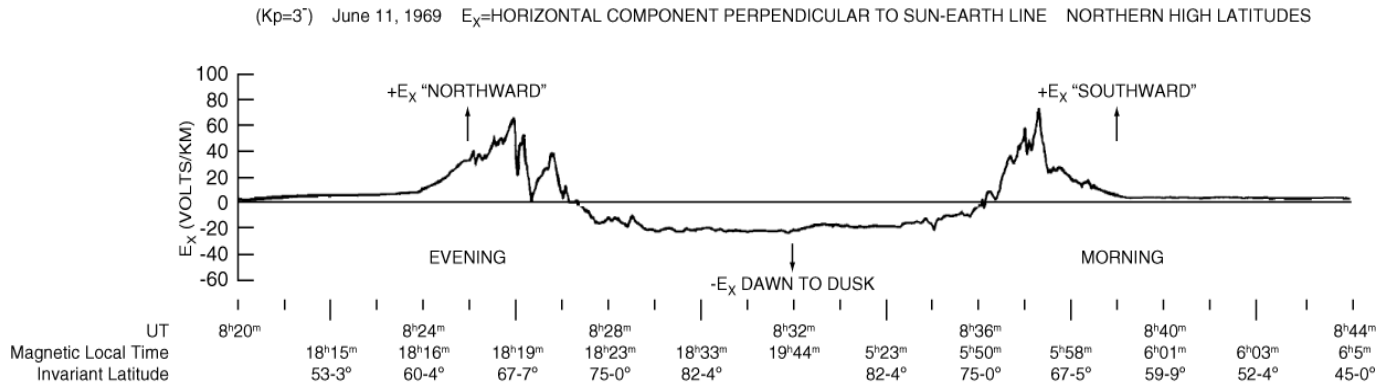
→ Effects of Forcing from Below

Solar wind/magnetosphere “drives” high latitude Ionosphere/Thermosphere ”system” which then feeds back on the magnetosphere!

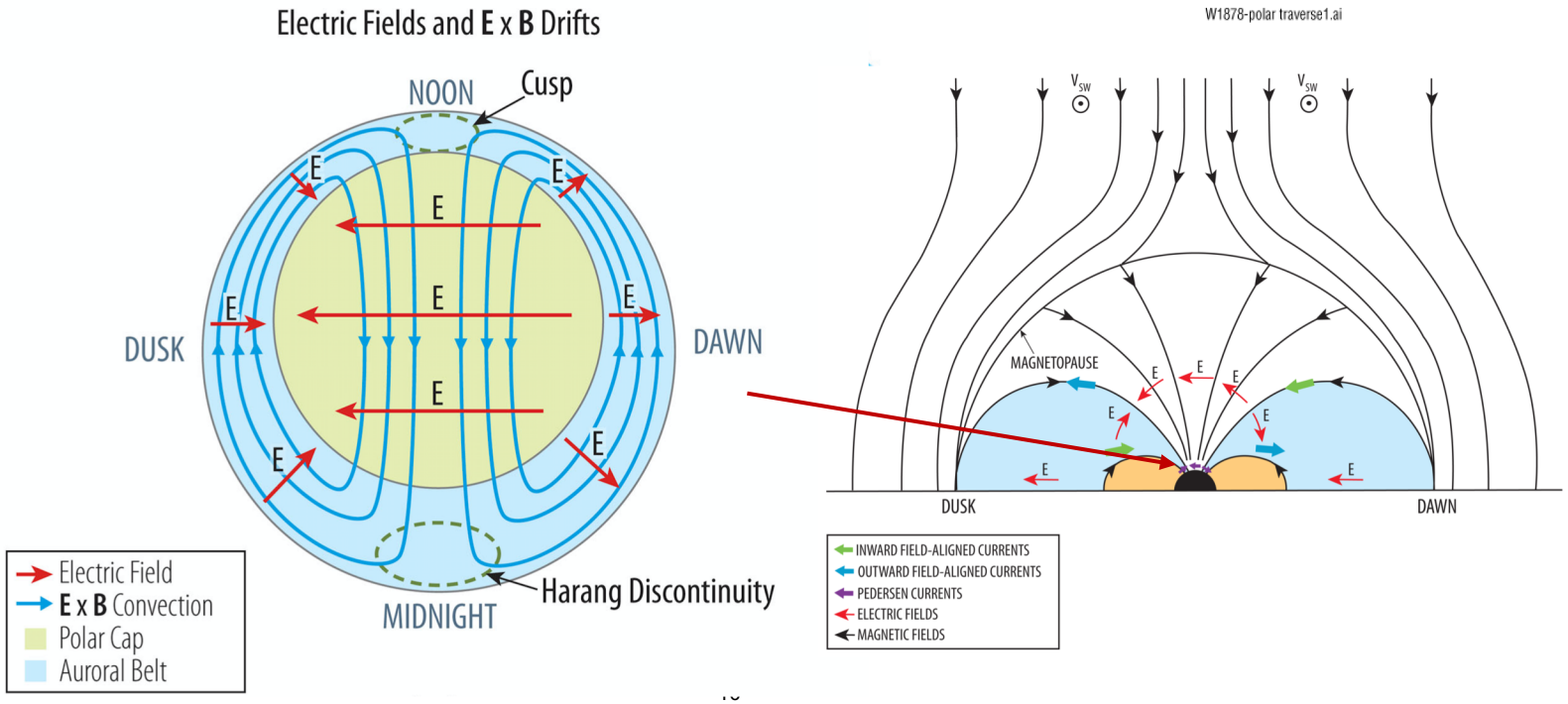




Single-axis E-field detector reveals fundamental 2-cell convection pattern

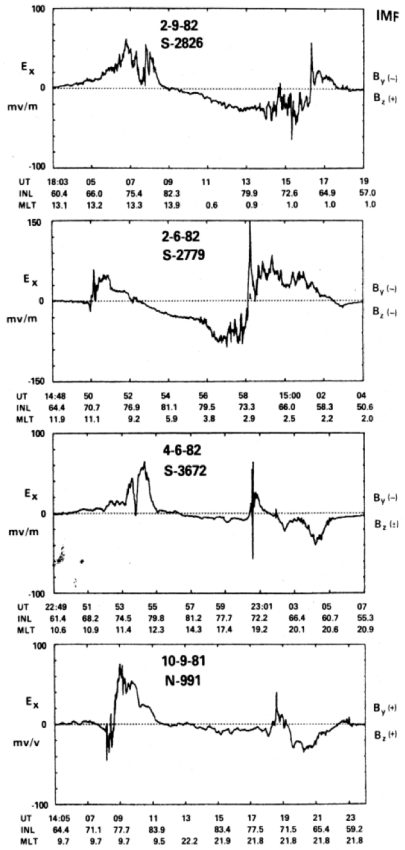


Heppner, 1972

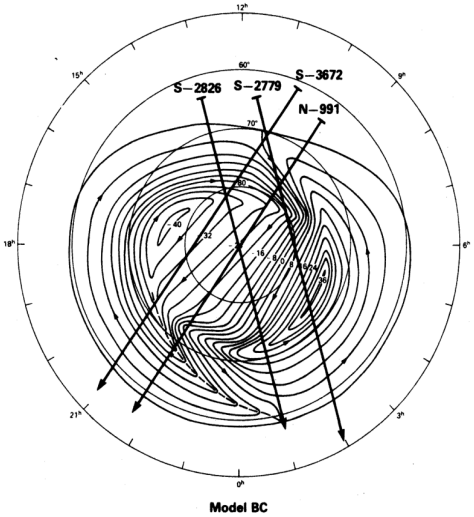


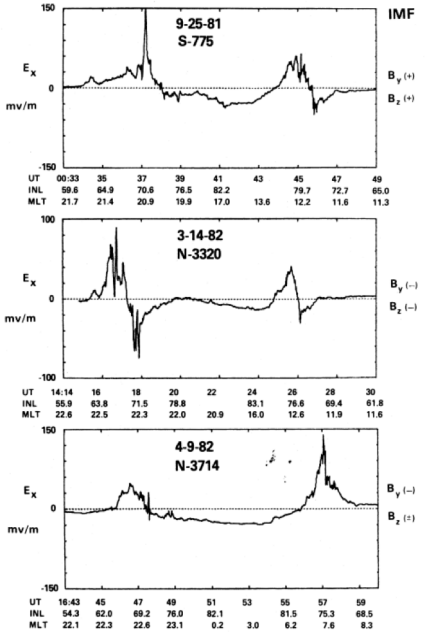
Empirical High Latitude Electric Field Patterns

Derived from N-S E-field Component on Separate DE-2 Passes

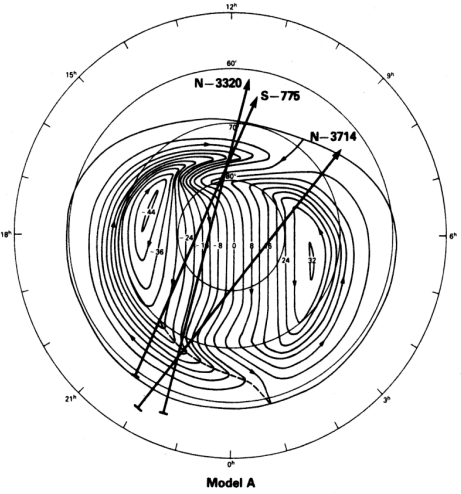


+ IMF By





– IMF By

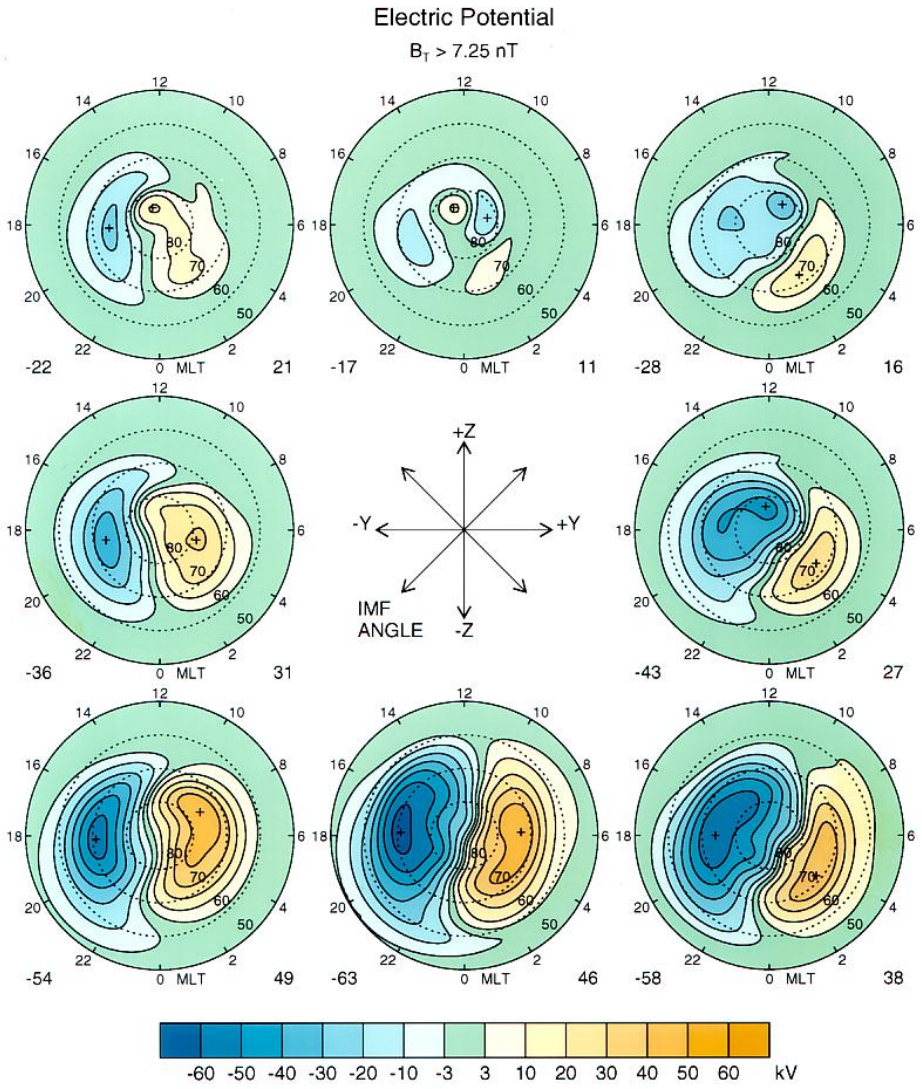


[Heppner and Maynard, 1987]

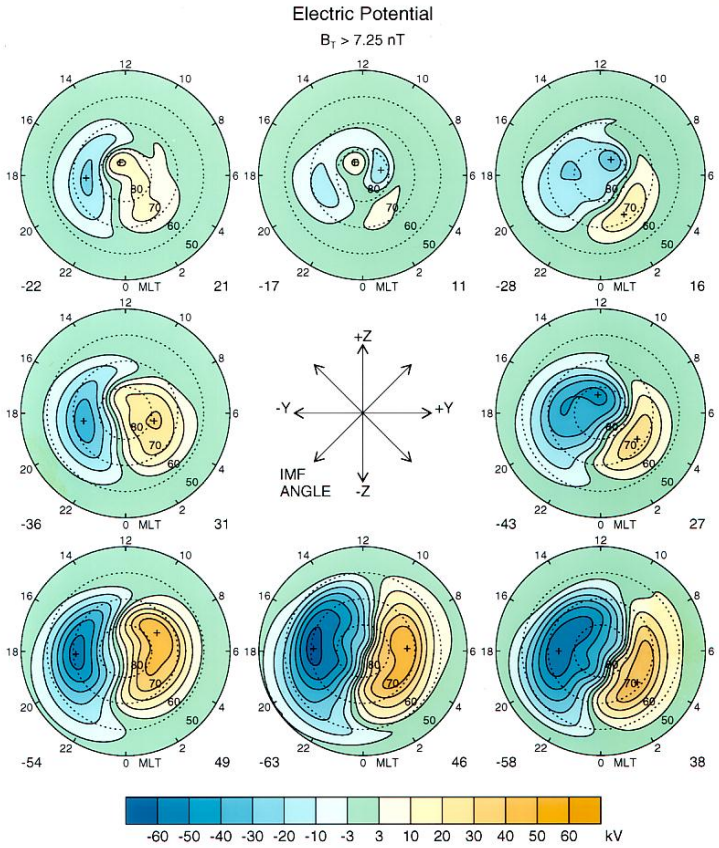
DE-2 Electric fields formed the basis of the Weimer Potential Model

The 1995 Weimer et al. paper used a least-error fit of spherical harmonic coefficients to derive the potential patterns from the sparse and randomly distributed measurements.

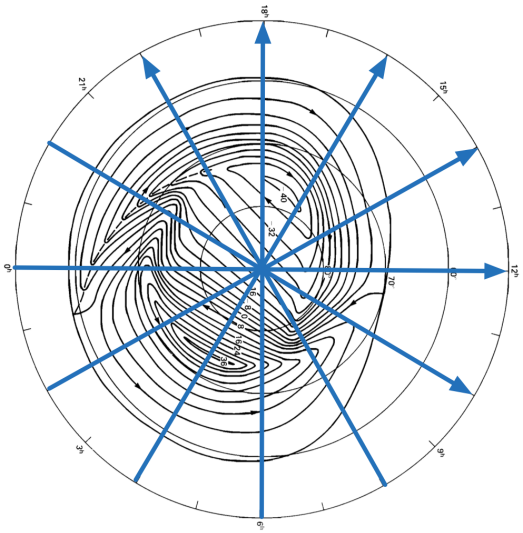
The passes were sorted into “bins” by IMF magnitude, clock angle, and dipole tilt angle.



GDC provides the next step towards modeling high latitude convection -- simultaneous observations at all local times….

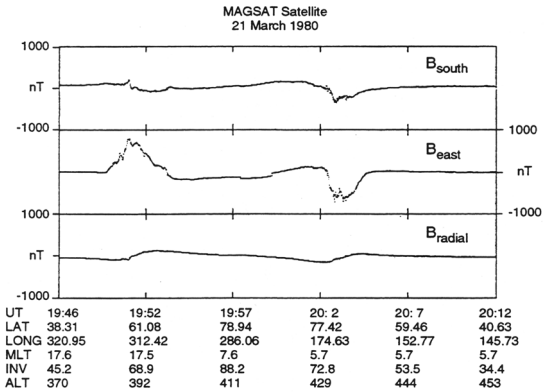


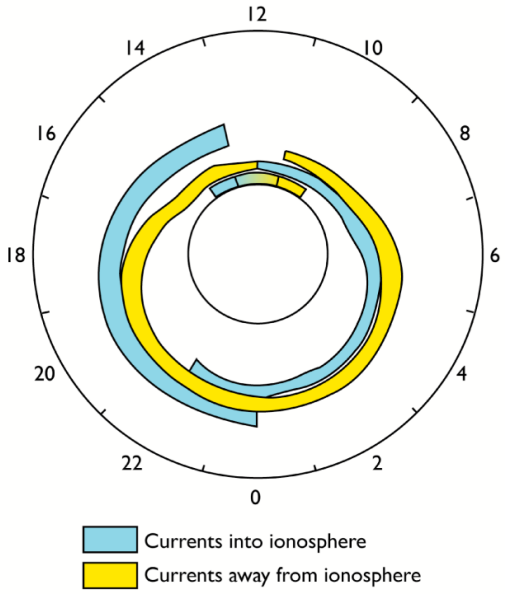
Static Averages binned by IMF



"Dynamic" convection patterns measured by simultaneous, multiple spacecraft

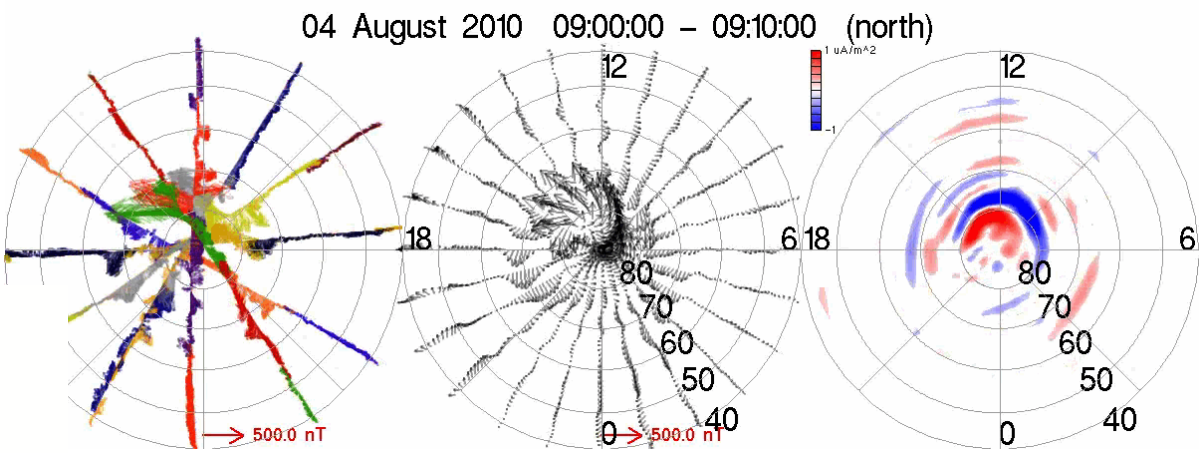
Magnetometer Measurements show Global Measurements of Field Aligned Currents





Iijima and Potemra, 1976

ΔB Spherical harmonic fit to **ΔB** Jr = **curl ΔB**

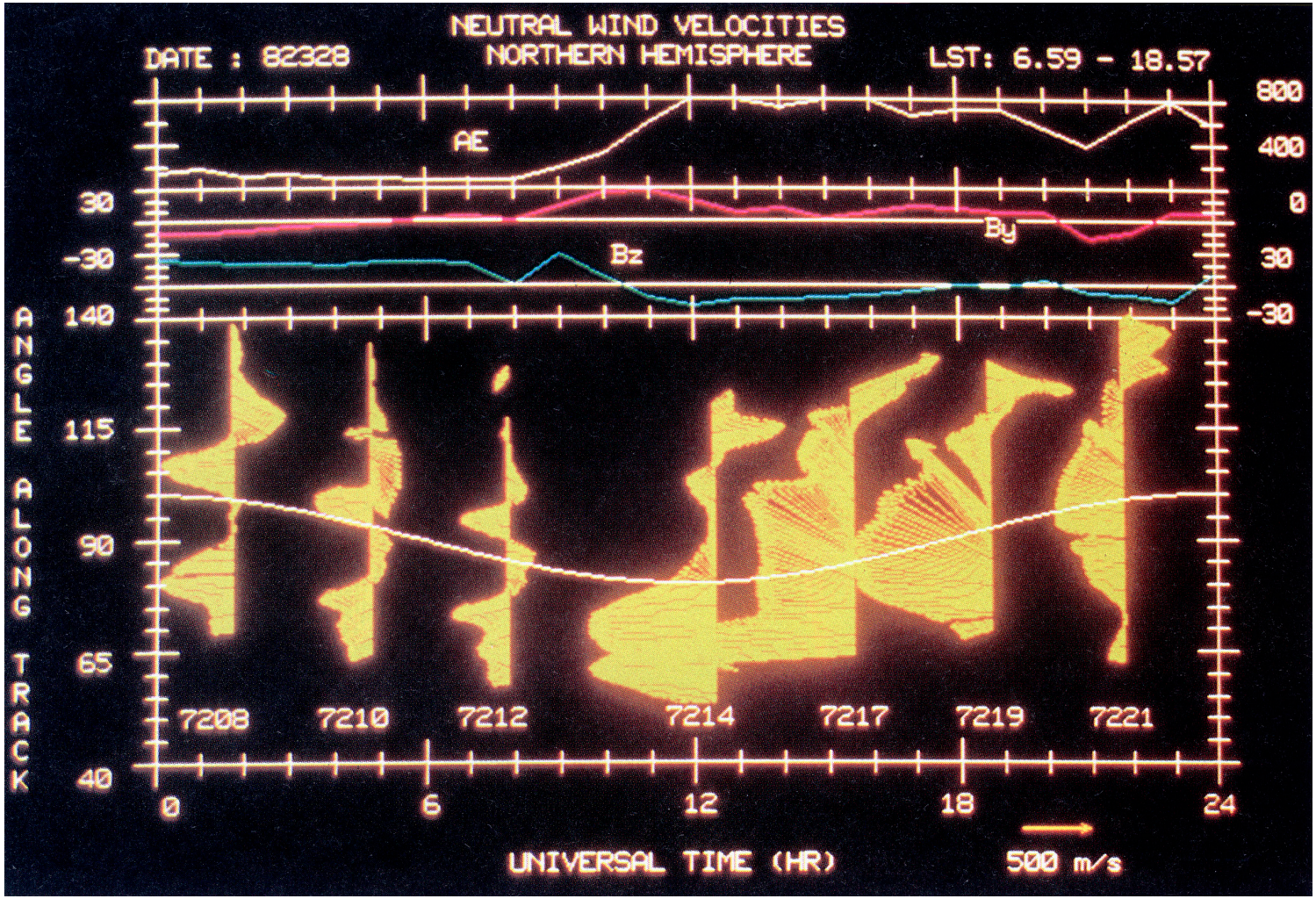


Courtesy B. Anderson

But why not also measure all of the key state variables…
(Neutrals) Un, Nn, Tn, Mn
(Ions) Vi, Ni, T, Mi,
E, **J** (**ΔB**), Energetic Electrons

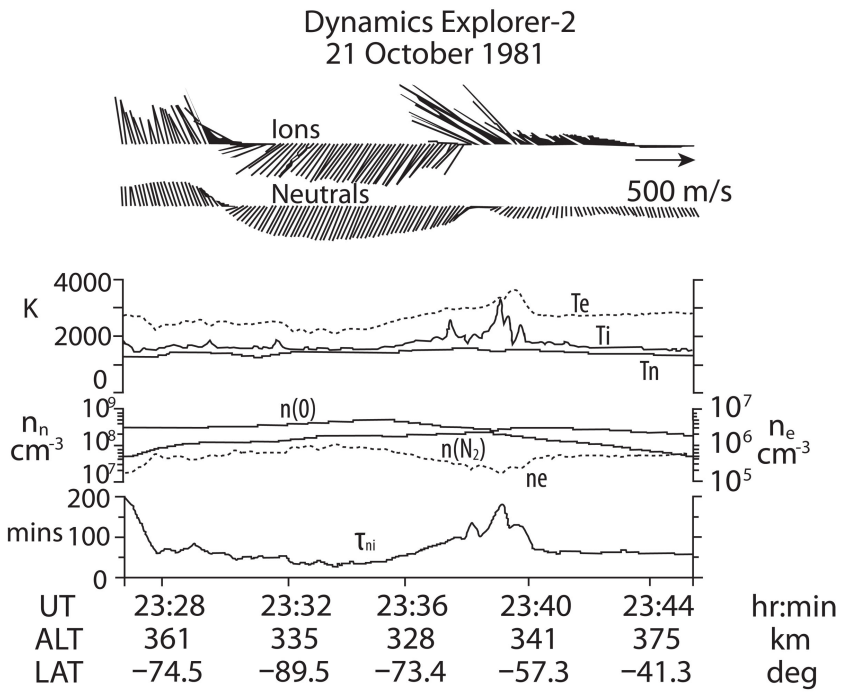
Earth's Upper Atmosphere is thrust into motion by the magnetosphere!

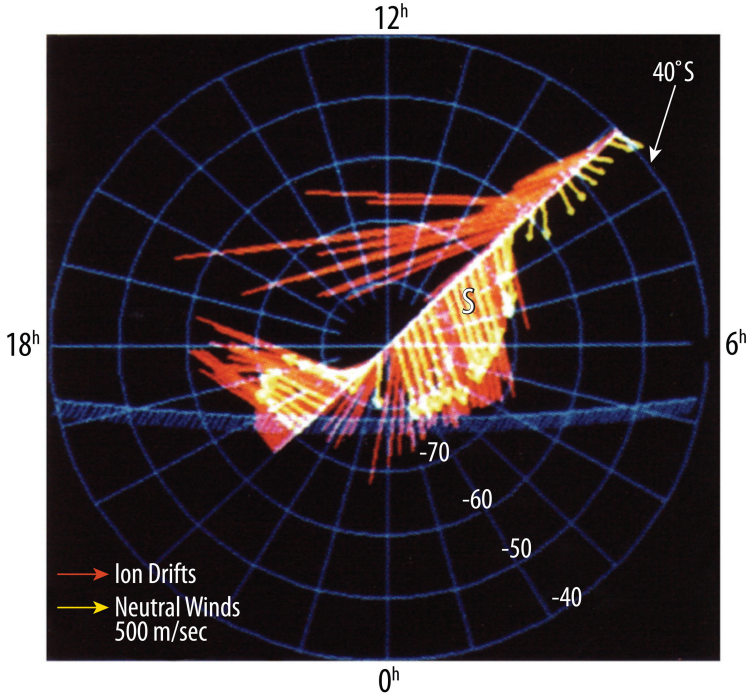
See in particular effects of Geomagnetic Storms!



[Killeen and Roble, 1988]

Simultaneous measurements of neutral winds and ion drifts on DE-2 as well as ion and neutral temperature and composition.



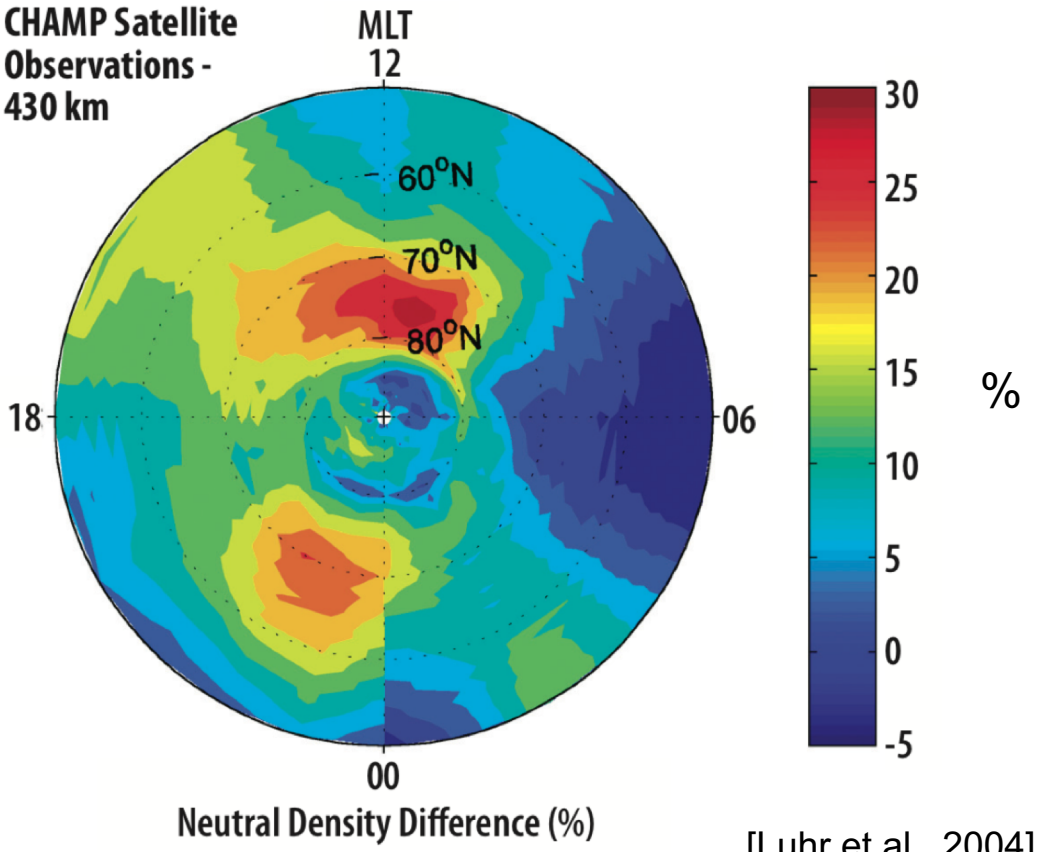


Killeen et al., 1984

DE-2 provided case studies

GDC will provide definitive, global, comprehensive measurements

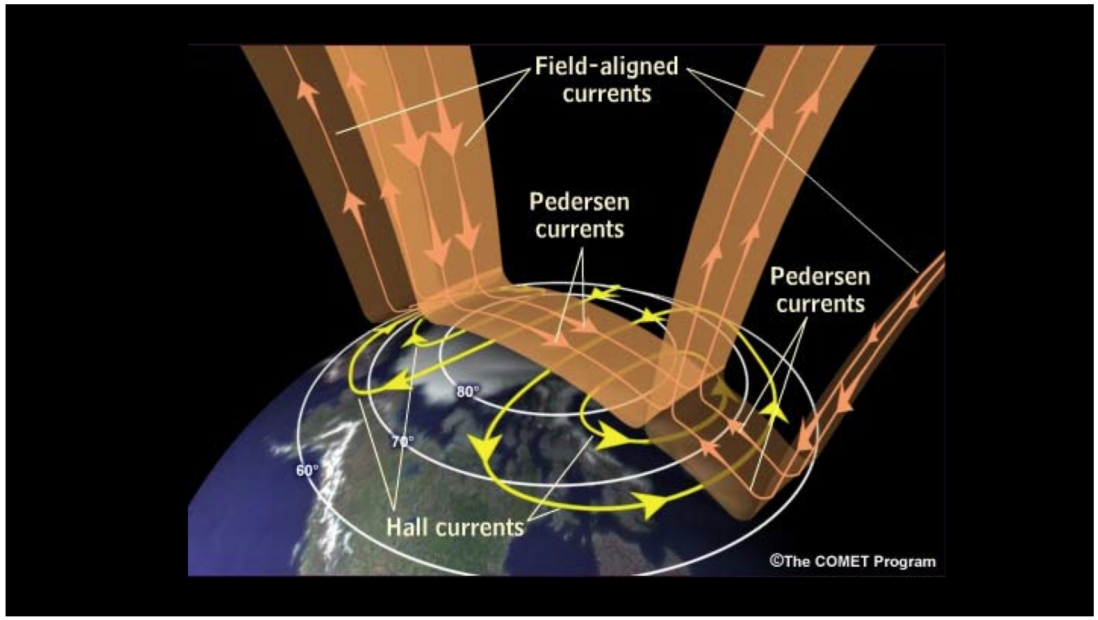
GDC will also reveal **neutral density structures** in the Ionosphere-Thermosphere system and what causes them

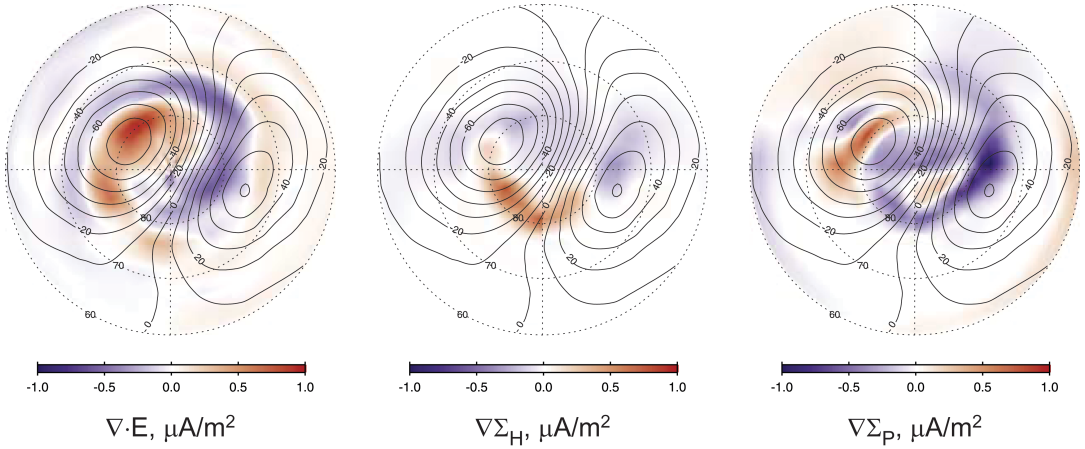


[Luhr et al., 2004]

Neutral density variations at high latitudes are poorly understood -- Thermospheric Upwelling? Driven by Joule Heating?

GDC measurements of currents, electric fields, conductivity (via precipitating energetic electrons), and neutral density will significantly advance our understanding of the high latitude current system

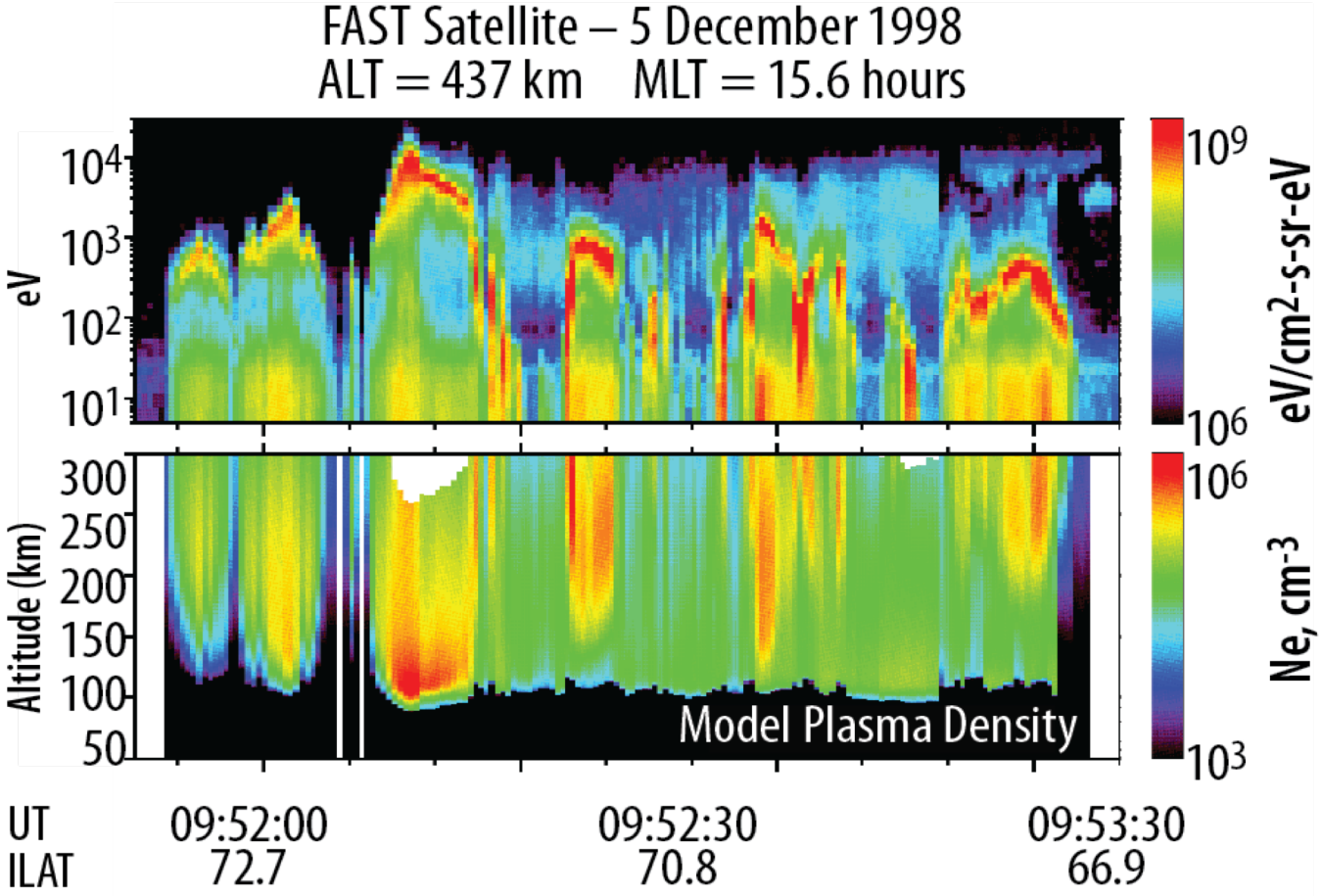




Model results of currents associated with gradients of electric fields, and Hall and Pedersen Conductivity

[after Lotko, personal communication]

Neutral density determines the creation of thermal plasma and current closure of field-aligned currents due to precipitating electrons



Upper panel: FAST Energetic Electron at 437 km
Lower panel: Model plasma density created by precipitating electrons

GDC Focus Areas/Science Objectives

→ Solar wind/Magnetosphere Forcing of the high latitude I/T system with feedback

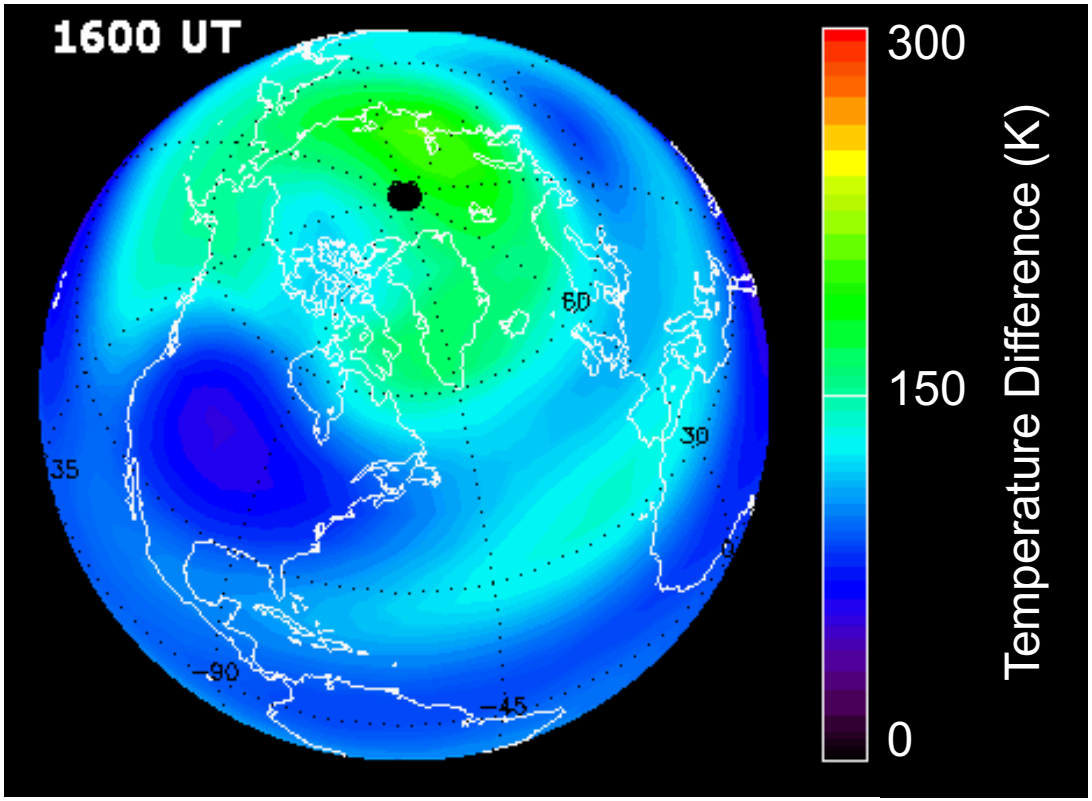
→ **Global Response of the ITM System to Geomagnetic Storms**

→ Causes of Large Scale Structuring of the Ionosphere and Upper Atmosphere

→ Effects of Forcing from Below

Global Response of IT System to Magnetic Storms

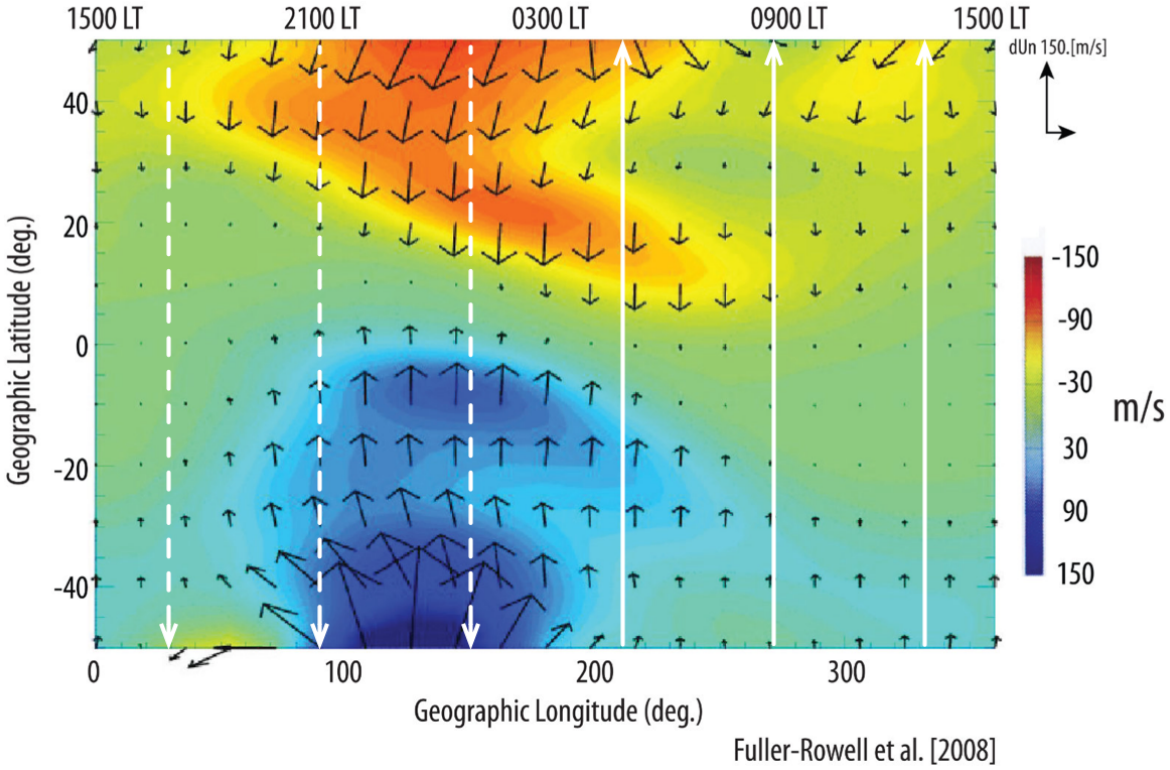
- Both observations and models show that the IT system responds globally to magnetic storms.
  - The response we observe is a consequence of many interconnected processes which result from ion-neutral, chemical-dynamical, and electrodynamic coupling.
  - Global responses vary with local time and are asymmetric between hemispheres.
- Current understanding is based on climatologies.
  - Insufficient to unravel the array of coupling and feedback processes that produce the global scale responses and their relationships to solar wind conditions.



Global Simulation of Magnetic Storm
Temperature at 350 km Altitude

Courtesy G. Lu

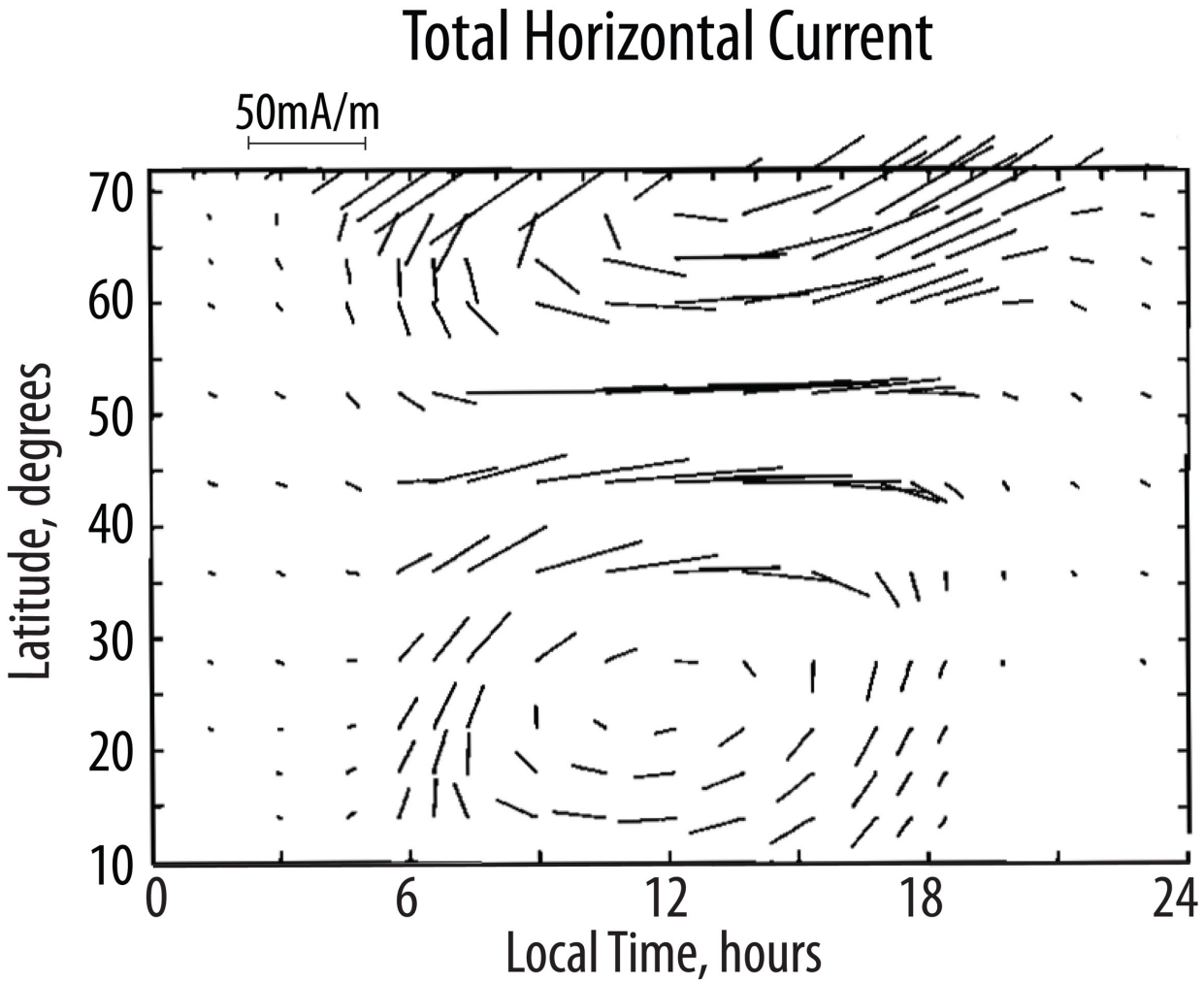
Neutral atmosphere is not only set in motion by the magnetosphere electric fields, but flows to lower latitudes!



Equatorward winds (Model results at 253 km) driven by auroral heating -- note the strong variations with local time (longitude)

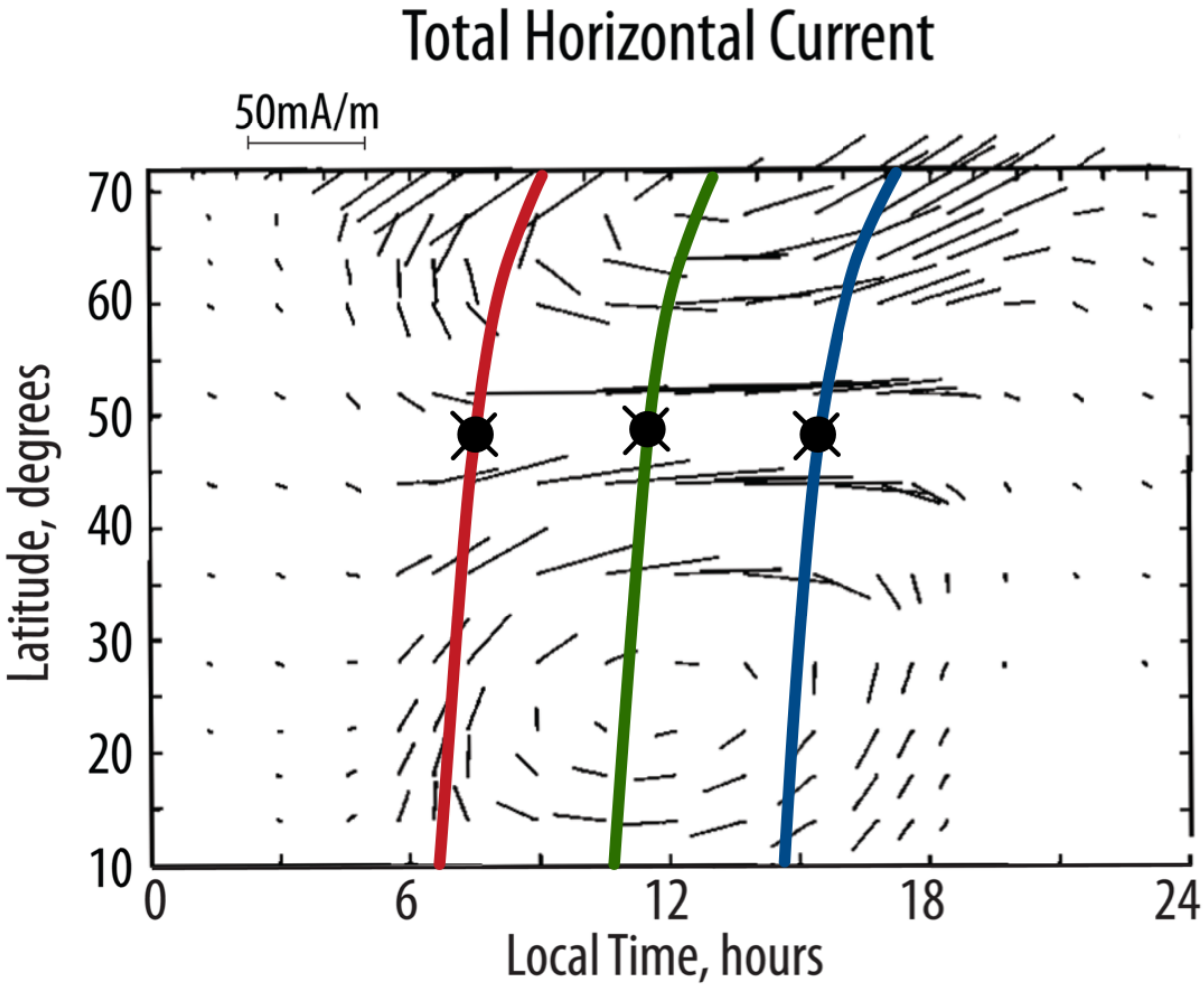
GDC will reveal how the mid and low latitude ionosphere/thermosphere respond to magnetic activity and storms, including extreme events

Currents, Winds and Plasma Velocity (Electric Fields) are Driven in Unknown ways during Magnetic Storms



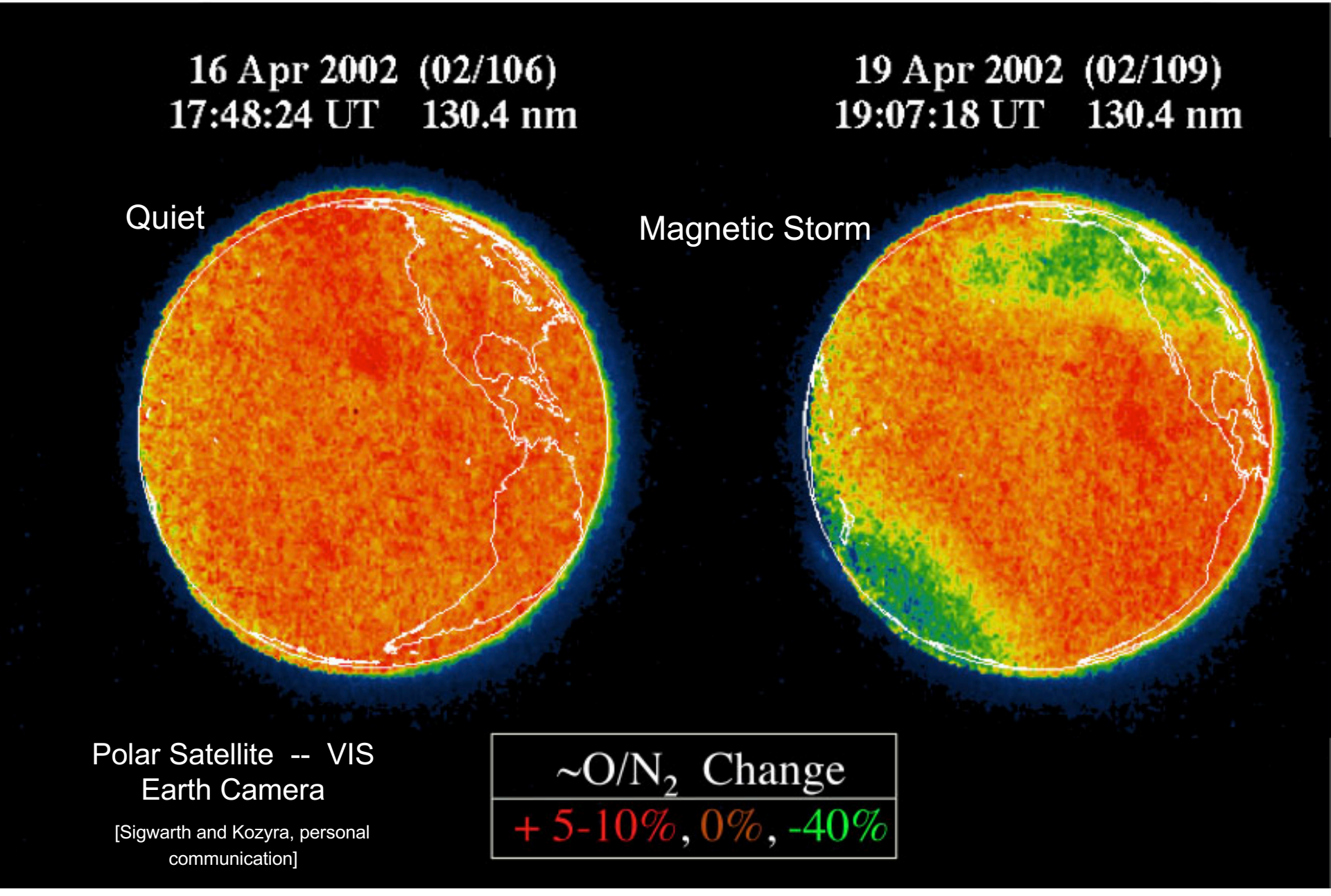
Blanc and Richmond, 1980

Currents and Plasma Velocity (Electric Fields) are Driven in Unknown ways during Magnetic Storms

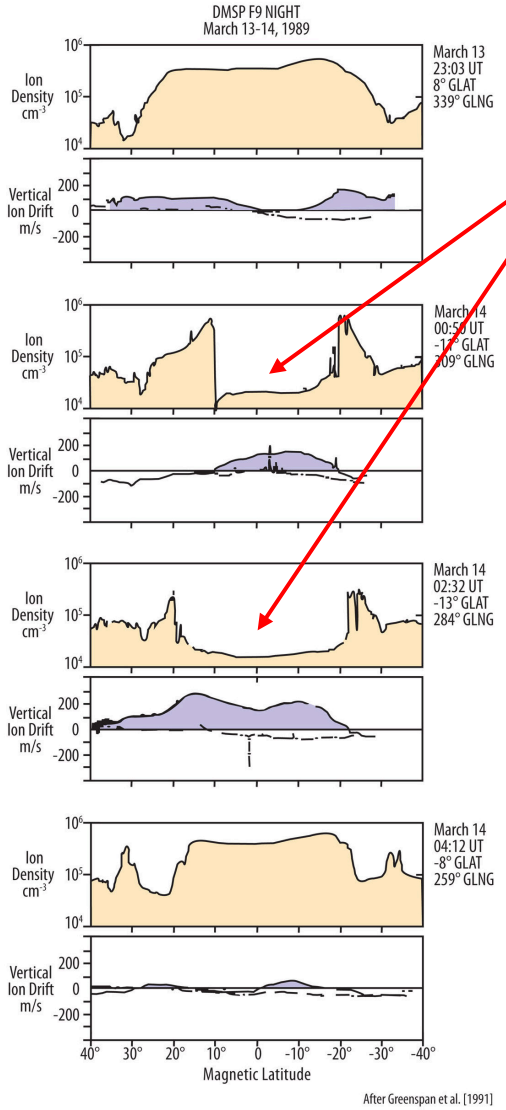


Blanc and Richmond, 1980

Indeed, the earth's entire upper atmosphere responds to magnetic storms in unpredictable ways!



During magnetic storms, the low latitude ionosphere often rises above 840 km (as shown by DMSP satellites), at least at 21:30 LT



Ionosphere "disappears" at low latitudes

→ Why? Penetration Electric fields?

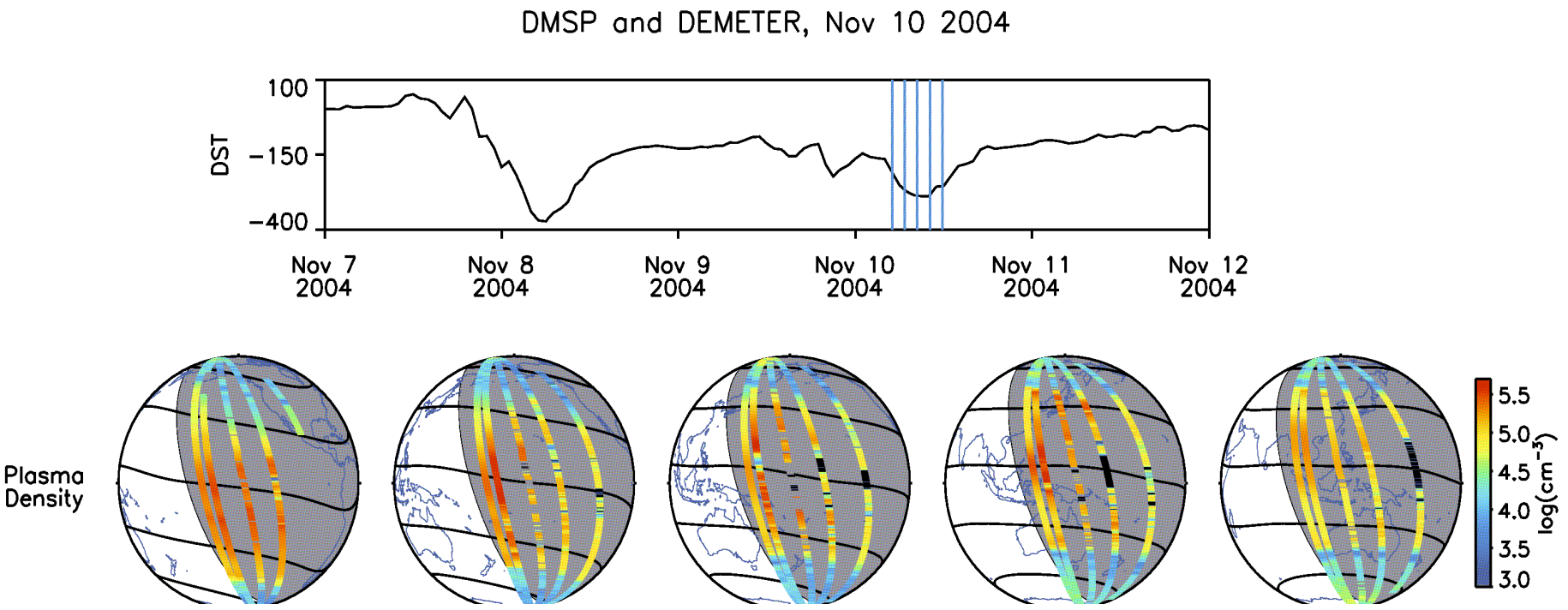
→ What happens at other local times?

→ What about the upper atmosphere?

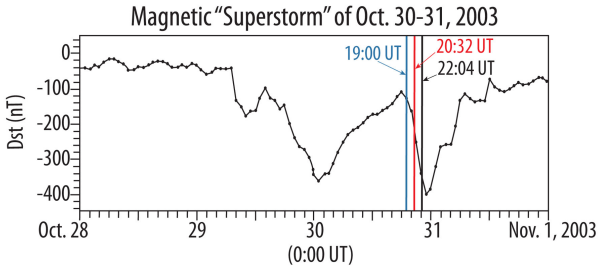
4 consecutive DMSP passes (100 minutes apart) near 21:30 L.T. show ionosphere rising above 840 km during magnetic storm

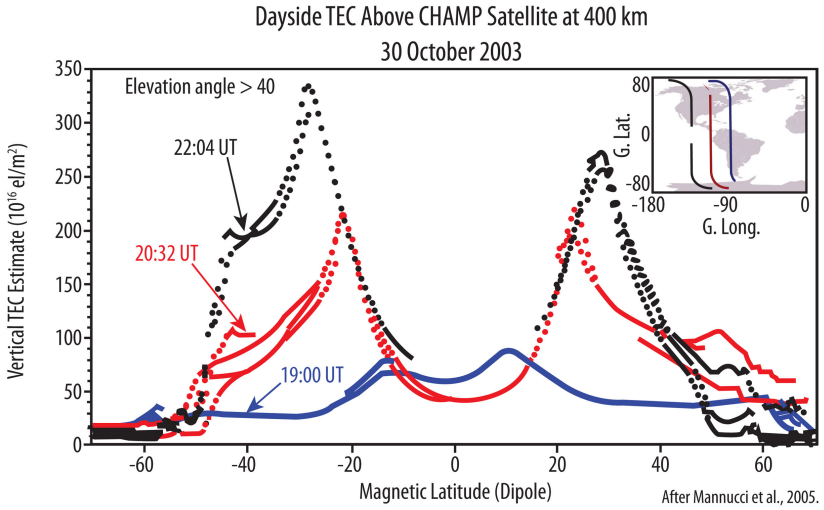
[Greenspan et al., 1991]

DMSP Multi-satellite observations of plasma density at 840 km



GDC will reveal how the mid and low latitude ionosphere responds to magnetic activity and storms, including extreme events.





Local times of these orbits -- 12:30 to 13:30 L.T.

TEC measurements (above 400 km) by GPS receiver on CHAMP on 3 successive orbits during magnetic "superstorm" of Oct. 30-31, 2003

GDC Focus Areas/Science Objectives

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→ Global Response of the ITM System to Geomagnetic Storms

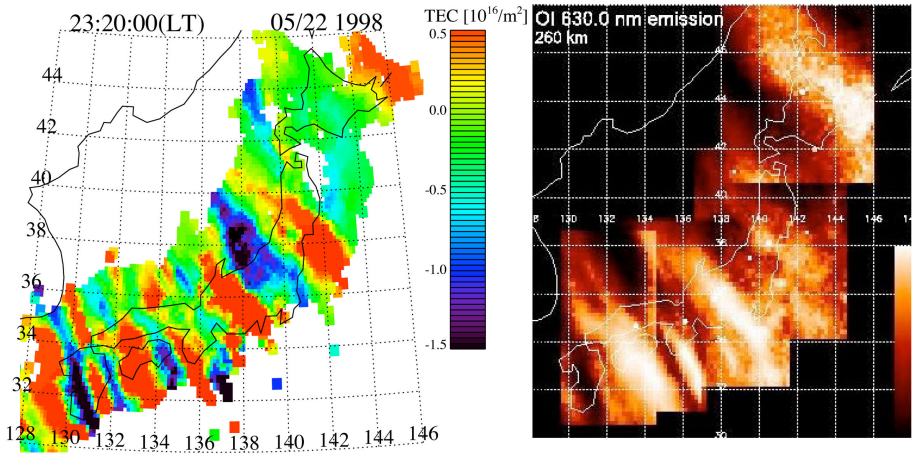
→ **Causes of Large Scale Structuring of the Ionosphere and Upper Atmosphere**

→ Effects of Forcing from Below

How do neutrals and plasmas interact to produce multi-scale structures in the Ionosphere-Thermosphere system?

Plasma

Neutral



Saito et al. [2001]

Ionosphere-Thermosphere is replete with traveling ionospheric disturbances which represent regional scale ion-neutral coupling

Storm-enhanced plasma density (SED) signatures believed connected to plasmasphere erosion and driven by sub-auroral electric fields from the inner magnetosphere.

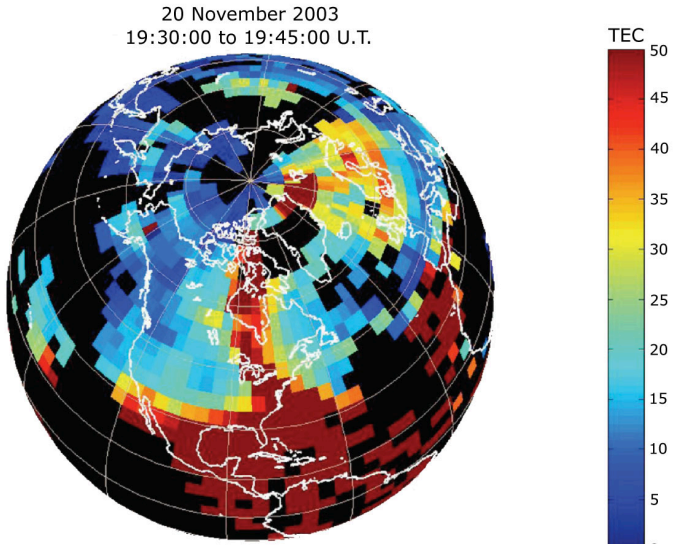
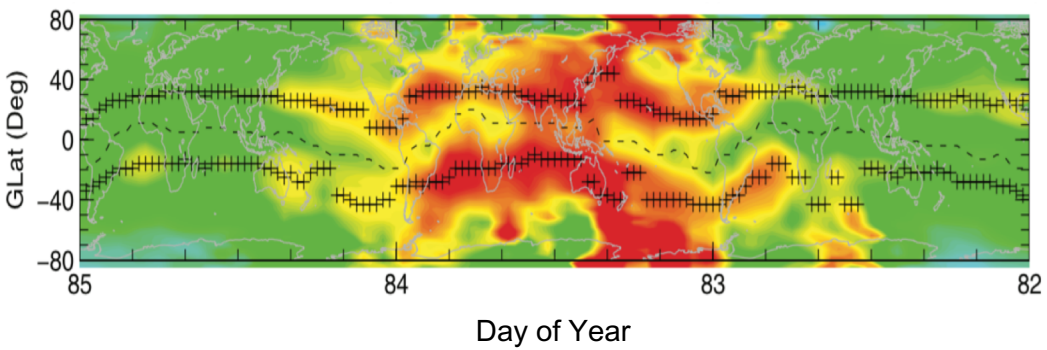


Figure courtesy A. Coster

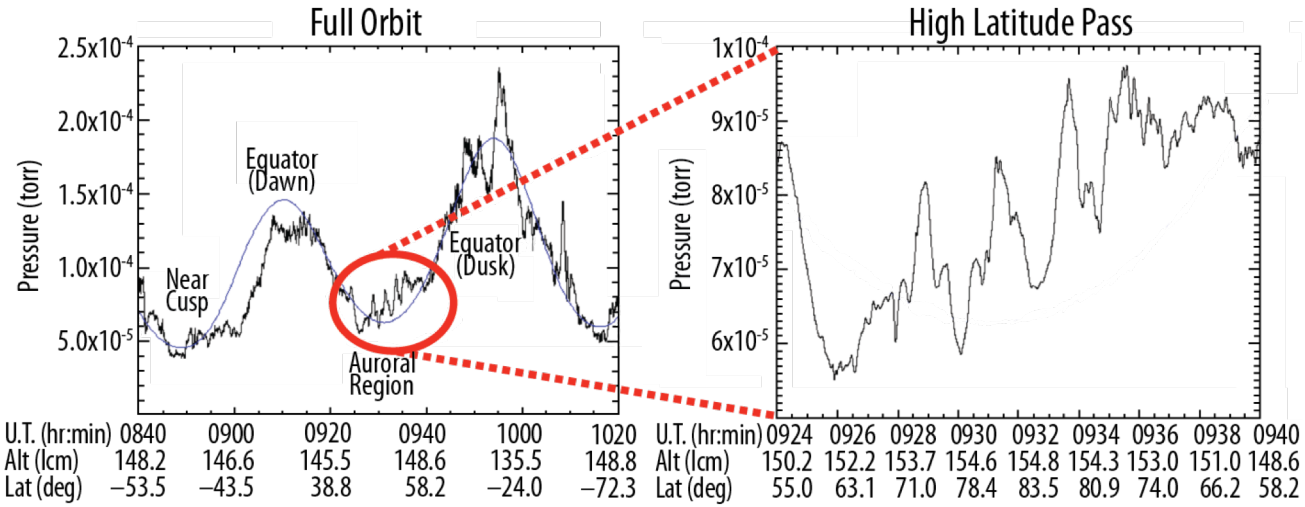
What drives atmospheric and ionospheric structure?

CHAMP Neutral density variations near 400 km



What is driving these? Are other longitudes/local times affected at the same time?

STREAK Satellite -- 28 June 2006



- GDC will reveal the structure in the atmosphere and determine its relation to structure in the driving energy sources.

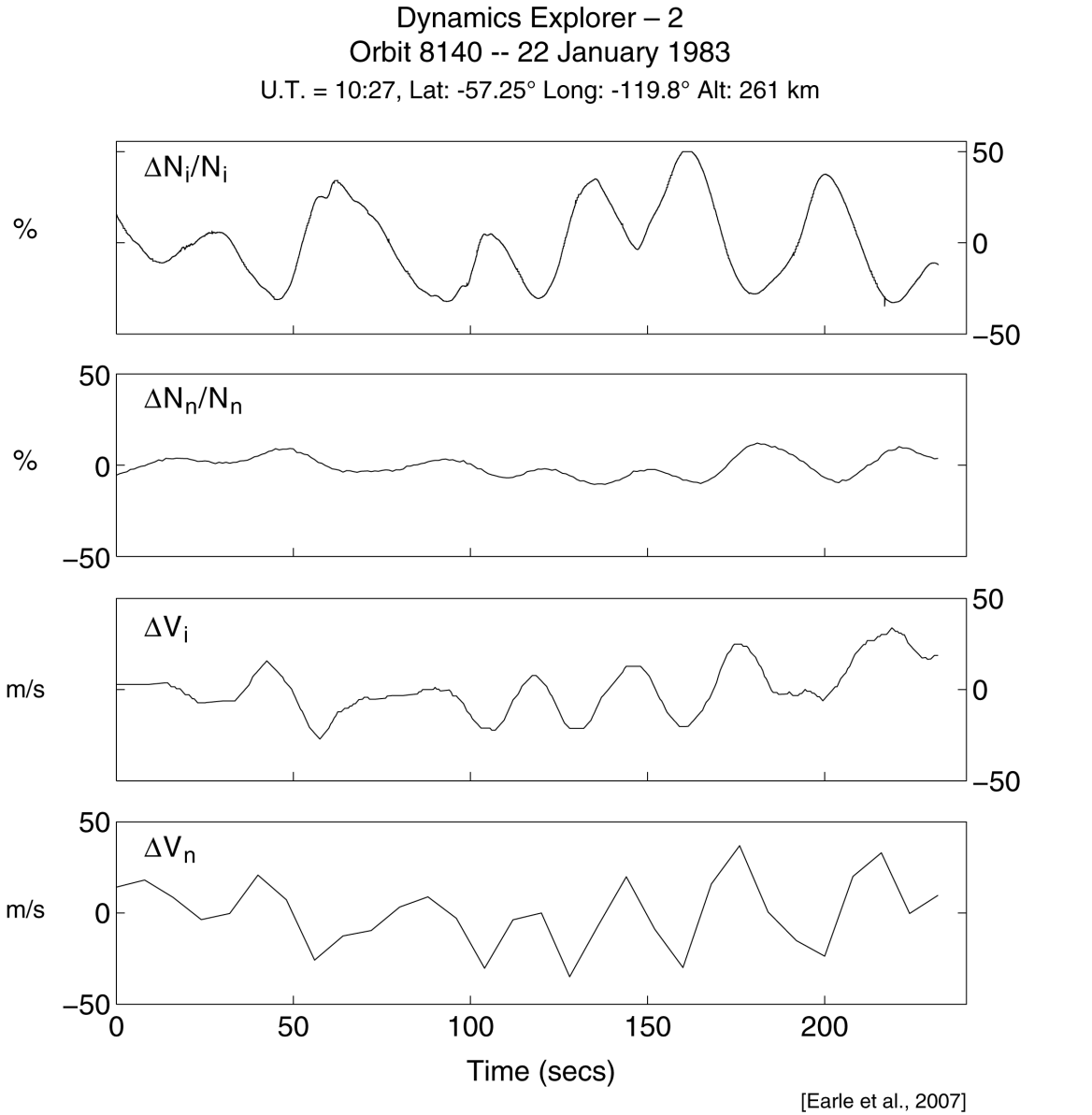
DE-2 Observations of *Gravity Waves* in neutral and ion measurements at 260 km at night.

$\lambda \geq 100$ km

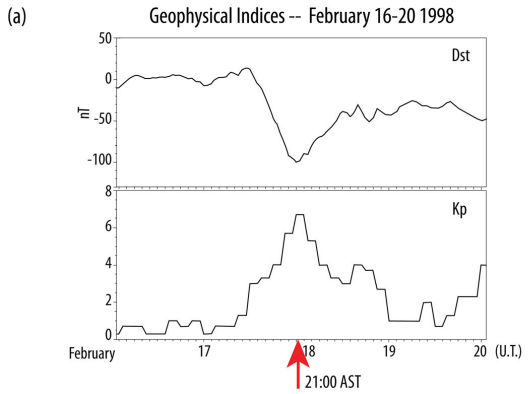
$V_\phi \sim 10$ m/s

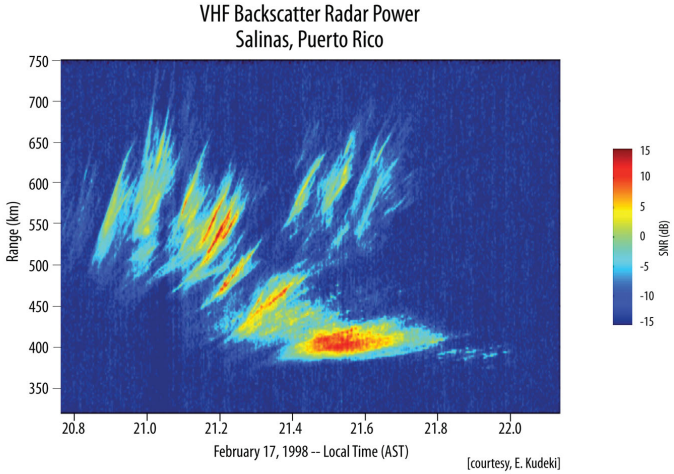
Consistent with upward propagation from below.

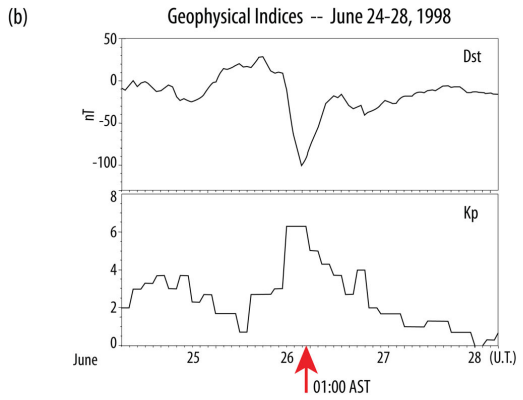
[Earle et al., *in press*, 2007]

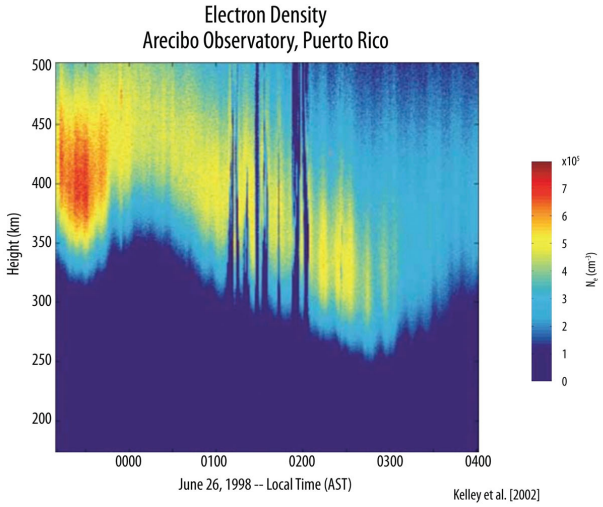


Mid-latitude “irregularities” associated with geomagnetic storms





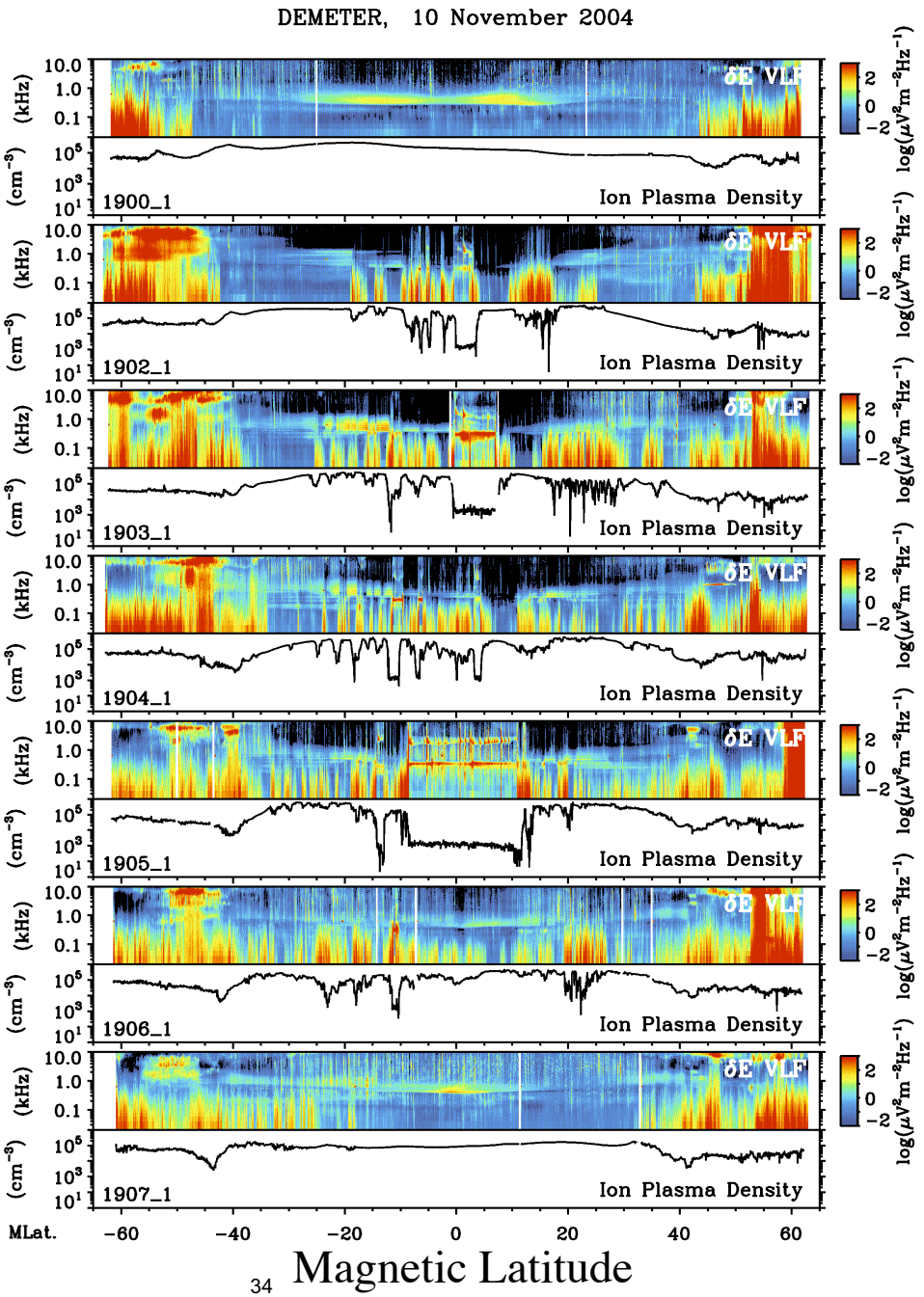




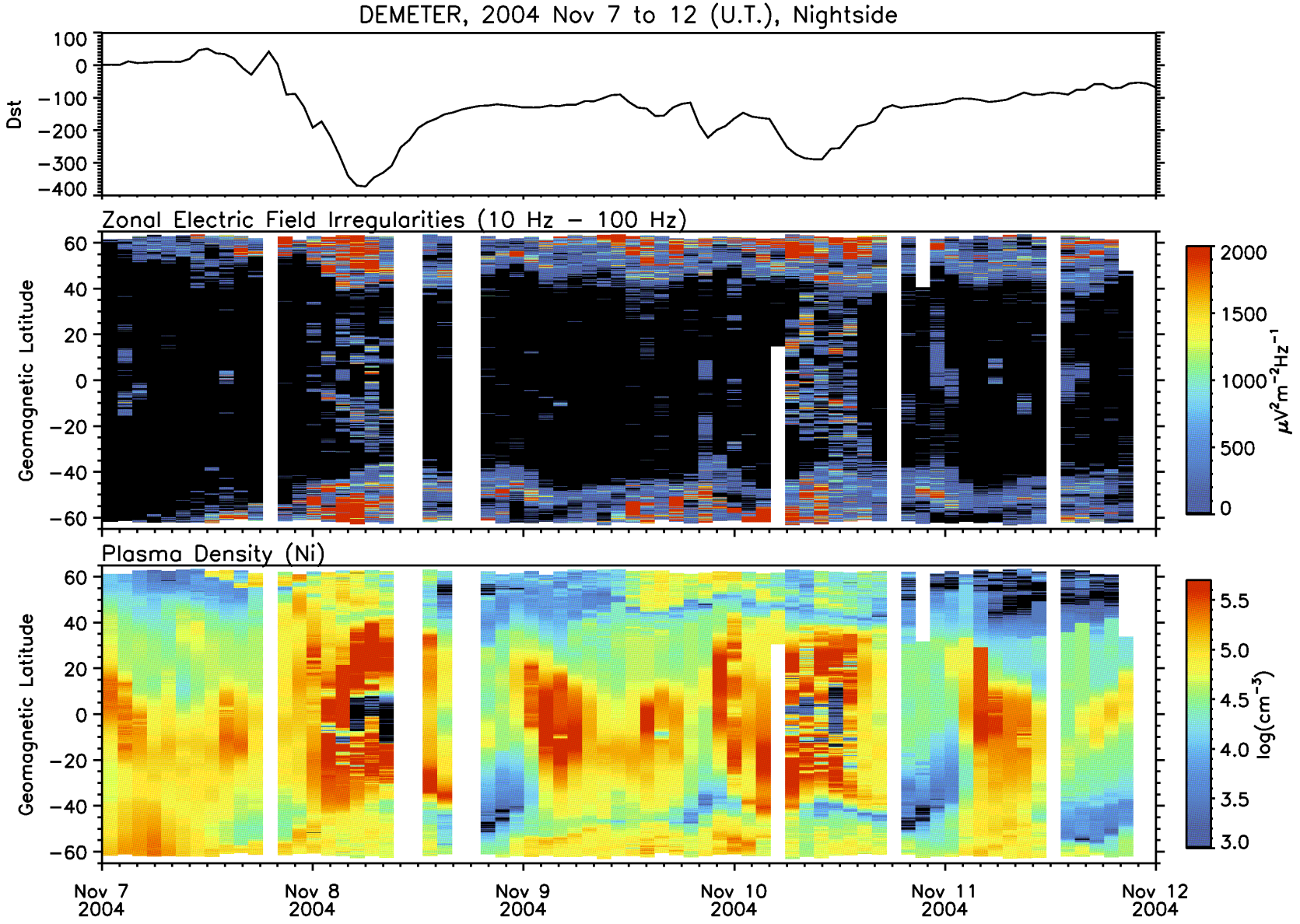
GDC will reveal how the mid and low latitude ionosphere develops large scale irregularities

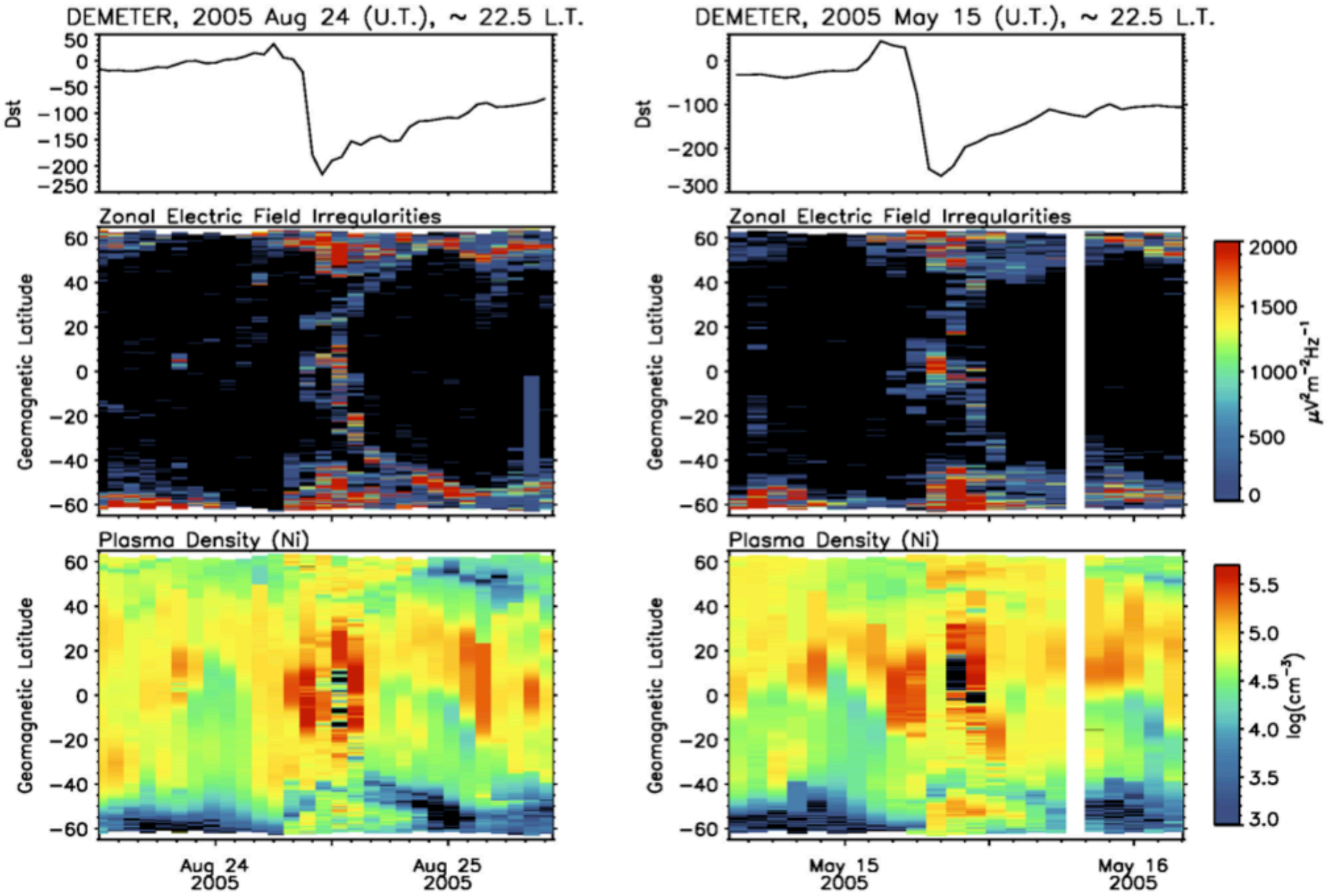
Consecutive DEMETER orbits at 22 h L.T. during major storm.

(~ 700 km)

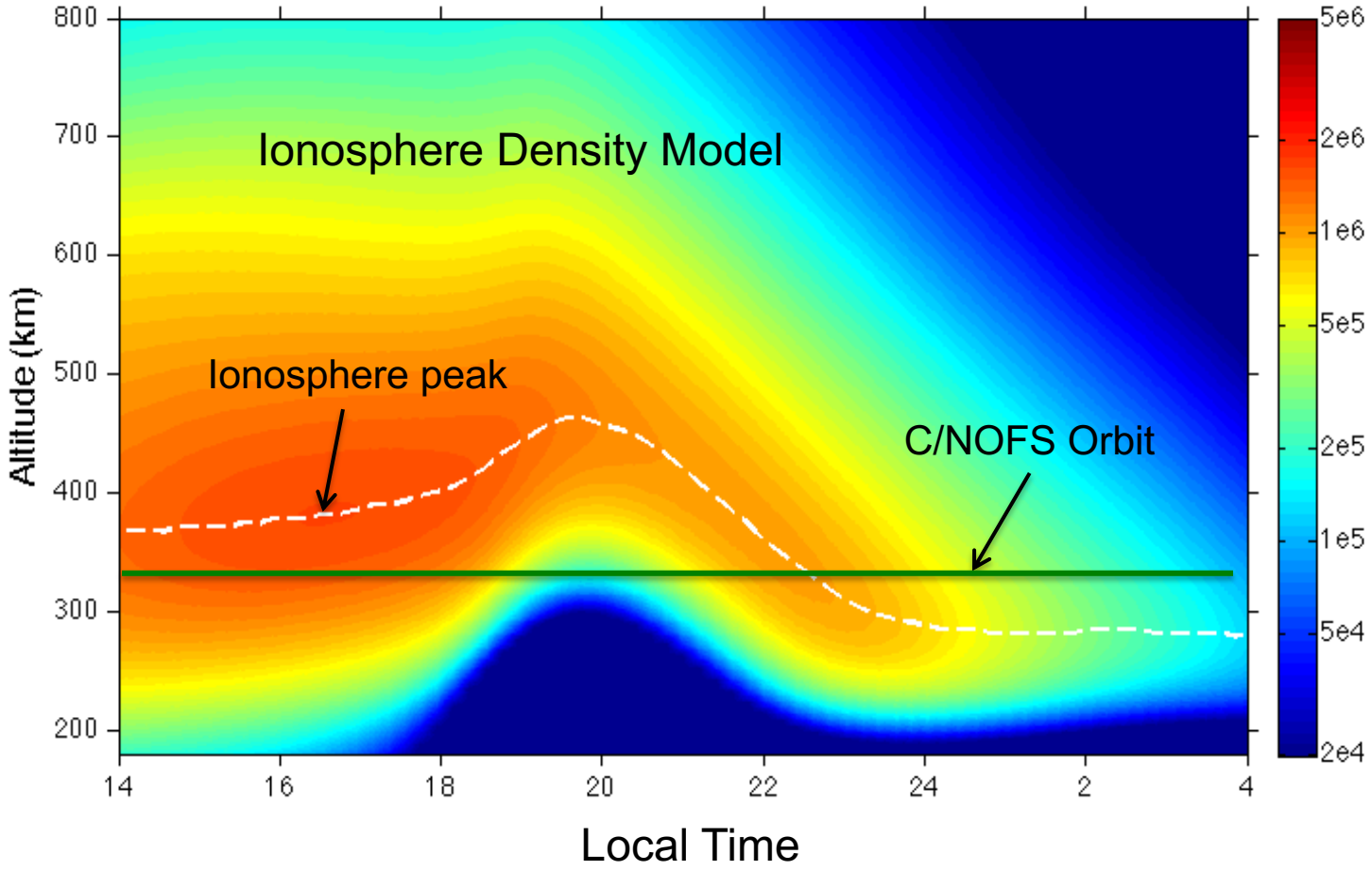


Missing one orbit.


DEMETER, 2004 Nov 7 to 12 (U.T.), Nightside
Dst
100
0
−100
−200
−300
−400
Zonal Electric Field Irregularities (10 Hz − 100 Hz)
Geomagnetic Latitude
60
40
20
0
−20
−40
−60
2000
1500
1000
500
0
μV²m⁻²Hz⁻¹
Plasma Density (Ni)
Geomagnetic Latitude
5.5
5.0
4.5
4.0
3.5
3.0
log(cm⁻³)
Nov 7 2004
Nov 8 2004
Nov 9 2004
Nov 10 2004
Nov 11 2004
Nov 12 2004

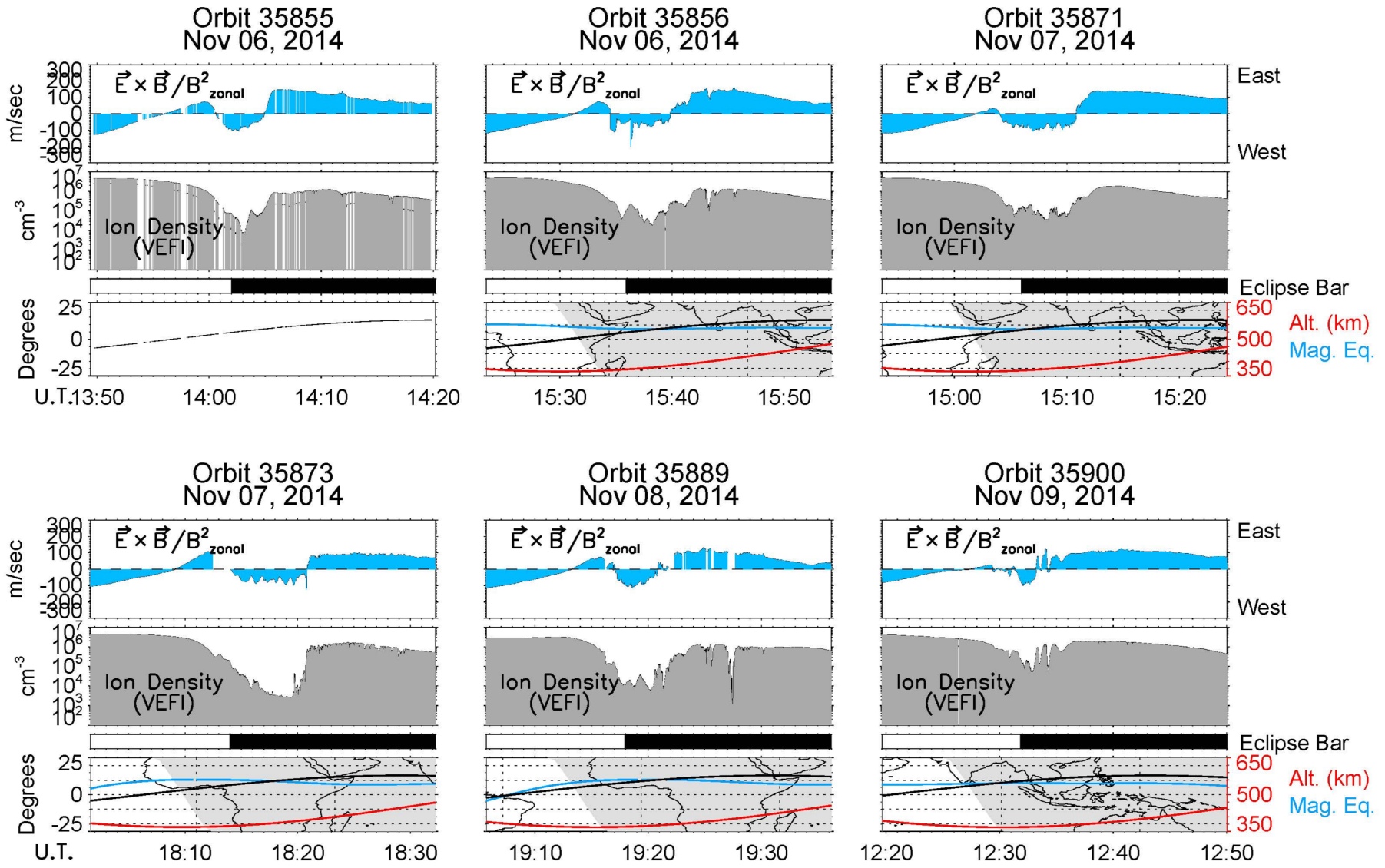

DEMETER, 2005 Aug 24 (U.T.), ~ 22.5 L.T.
Dst
50
0
−50
−100
−150
−200
−250
Zonal Electric Field Irregularities
Geomagnetic Latitude
60
40
20
0
−20
−40
−60
Plasma Density (Ni)
Aug 24
2005
Aug 25
2005
DEMETER, 2005 May 15 (U.T.), ~ 22.5 L.T.
0
−100
−200
−300
2000
1500
1000
500
0
$\mu V^2 m^{-2} Hz^{-1}$
5.5
5.0
4.5
4.0
3.5
3.0
log(cm^{-3})
May 15
2005
May 16
2005

Spacecraft traversals below the Base of the F-region Reveals new physics



Ionosphere density is elevated at sunset

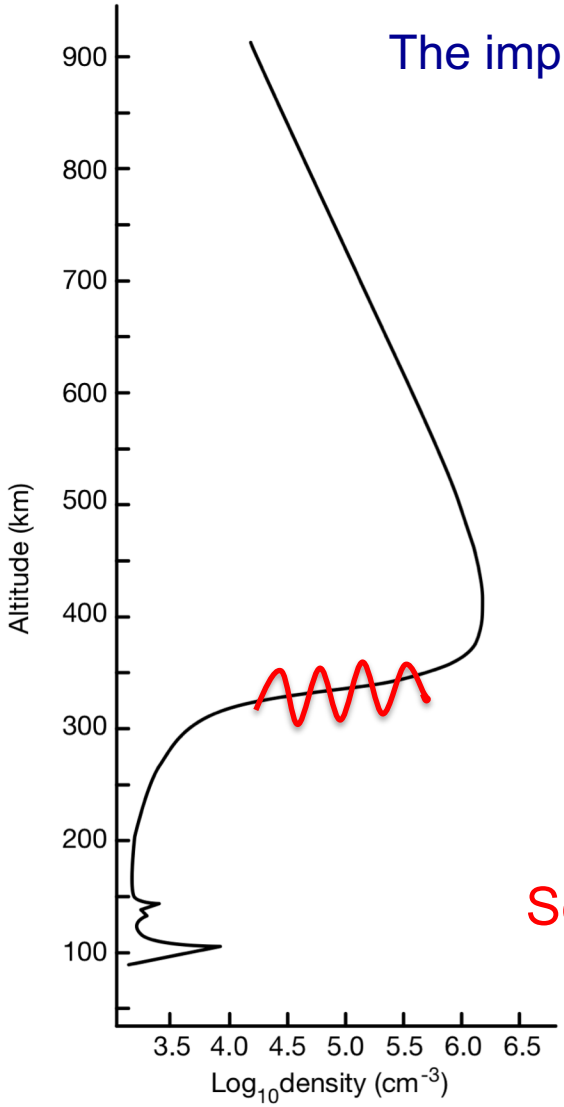
C/NOFS VEFI Observations



CN-4312-0248-5878-60R-DGH-02-N, CN-4312-0429-5879-70R-DGH-00-N
c:\cnofs\carmen\plots\2014-11-07_18_01_36_to_2014-11-07_18_32_15_35873_Esolved_DP_2-axis_solution_Robs_Request_259_ExB.ps
Tue Feb 10 15:09:38 2015 cl
Esolved_DP, two-axis solutions

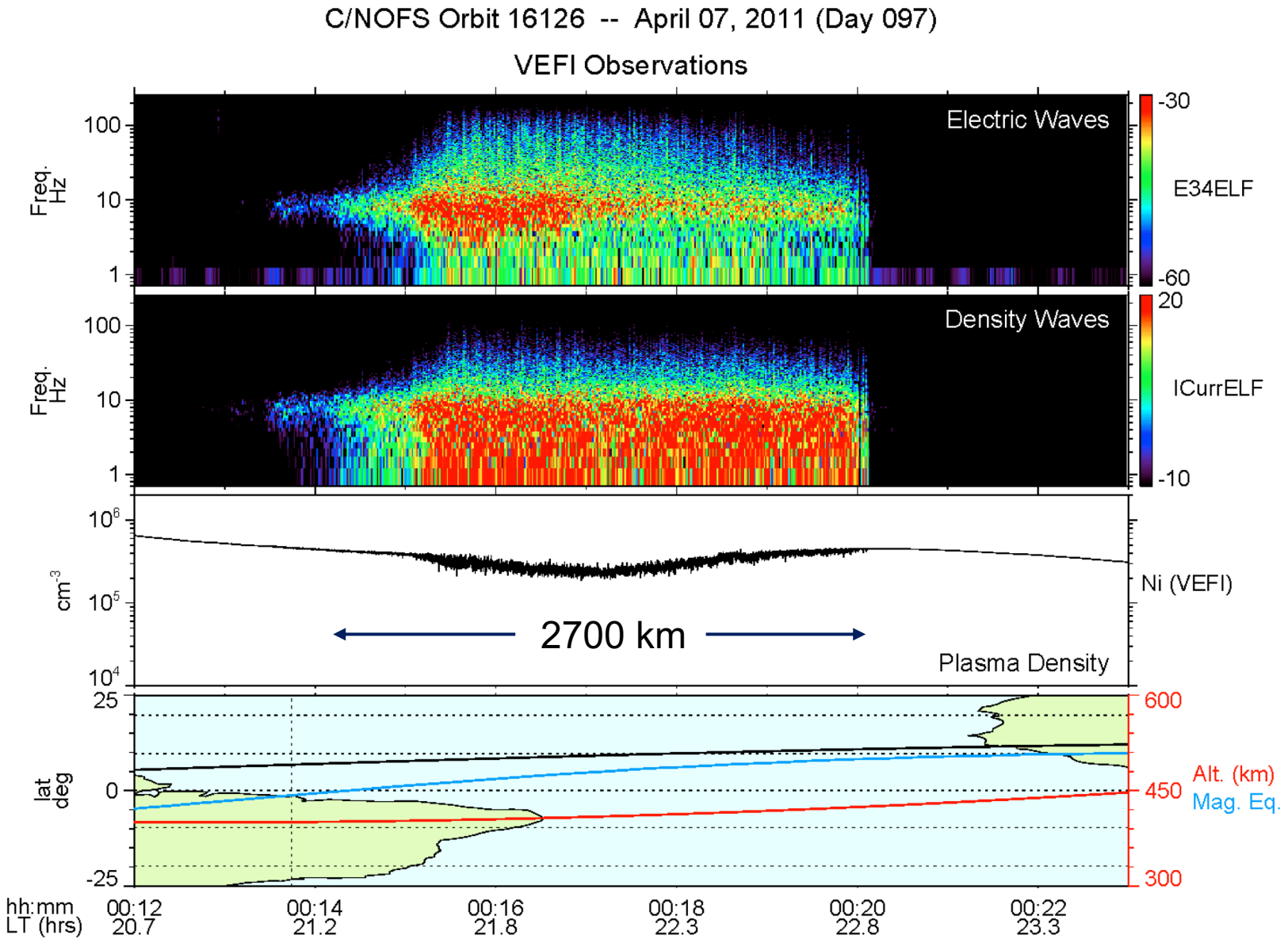
At sunset, the ionosphere below the F-peak flows in a reversed zonal direction than the topside.

The implications for the creation of instabilities are very important…



Does the shear drive instabilities?

Search for large scale undulations on bottomside…



CN-110407
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Ni method 3
Tue Nov 28 17:10:43 2017

Figure 23

GDC Focus Areas/Science Objectives

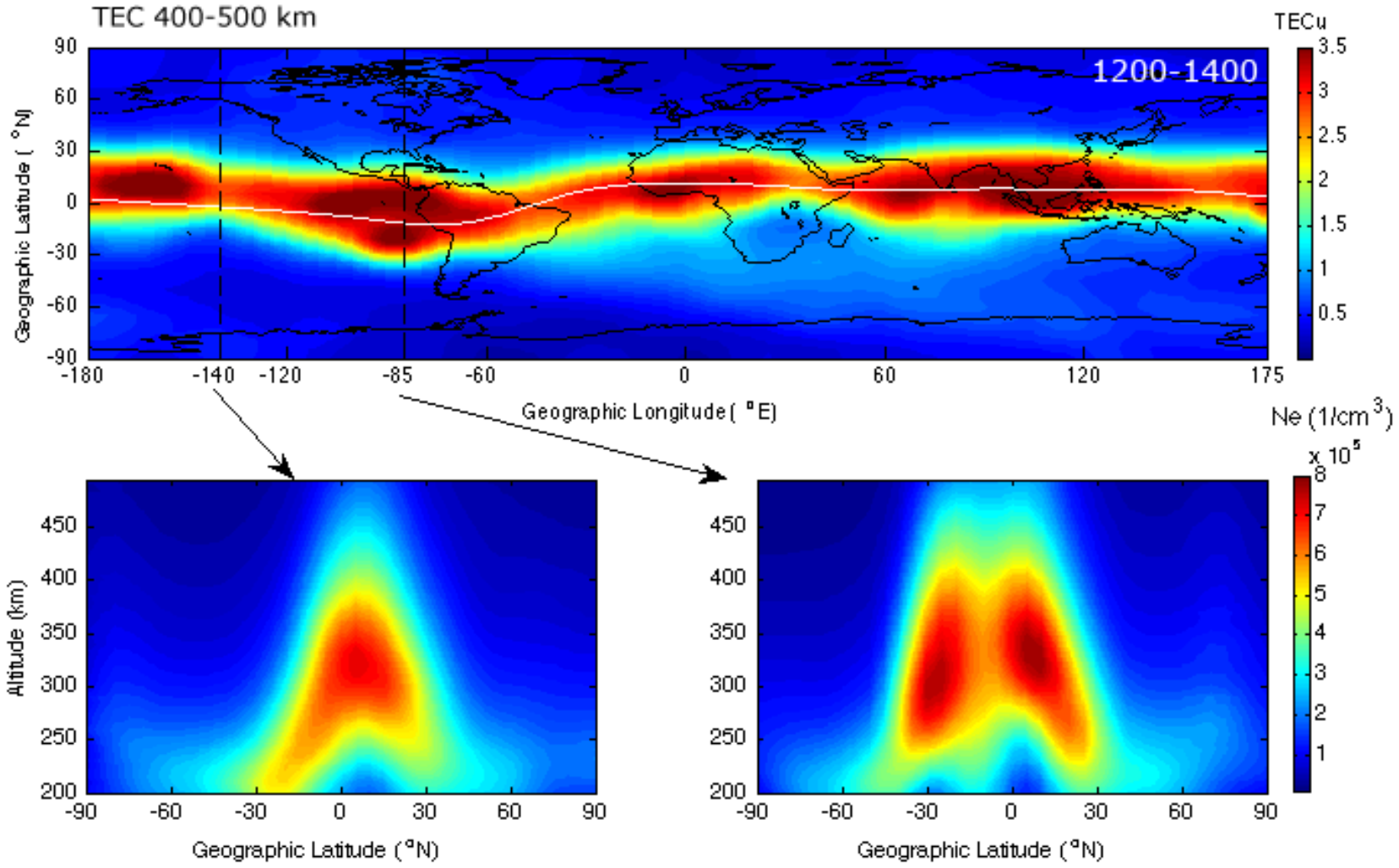
→ Solar wind/Magnetosphere Forcing of the high latitude I/T system with feedback

→ Global Response of the ITM System to Geomagnetic Storms

→ Causes of Large Scale Structuring of the Ionosphere and Upper Atmosphere

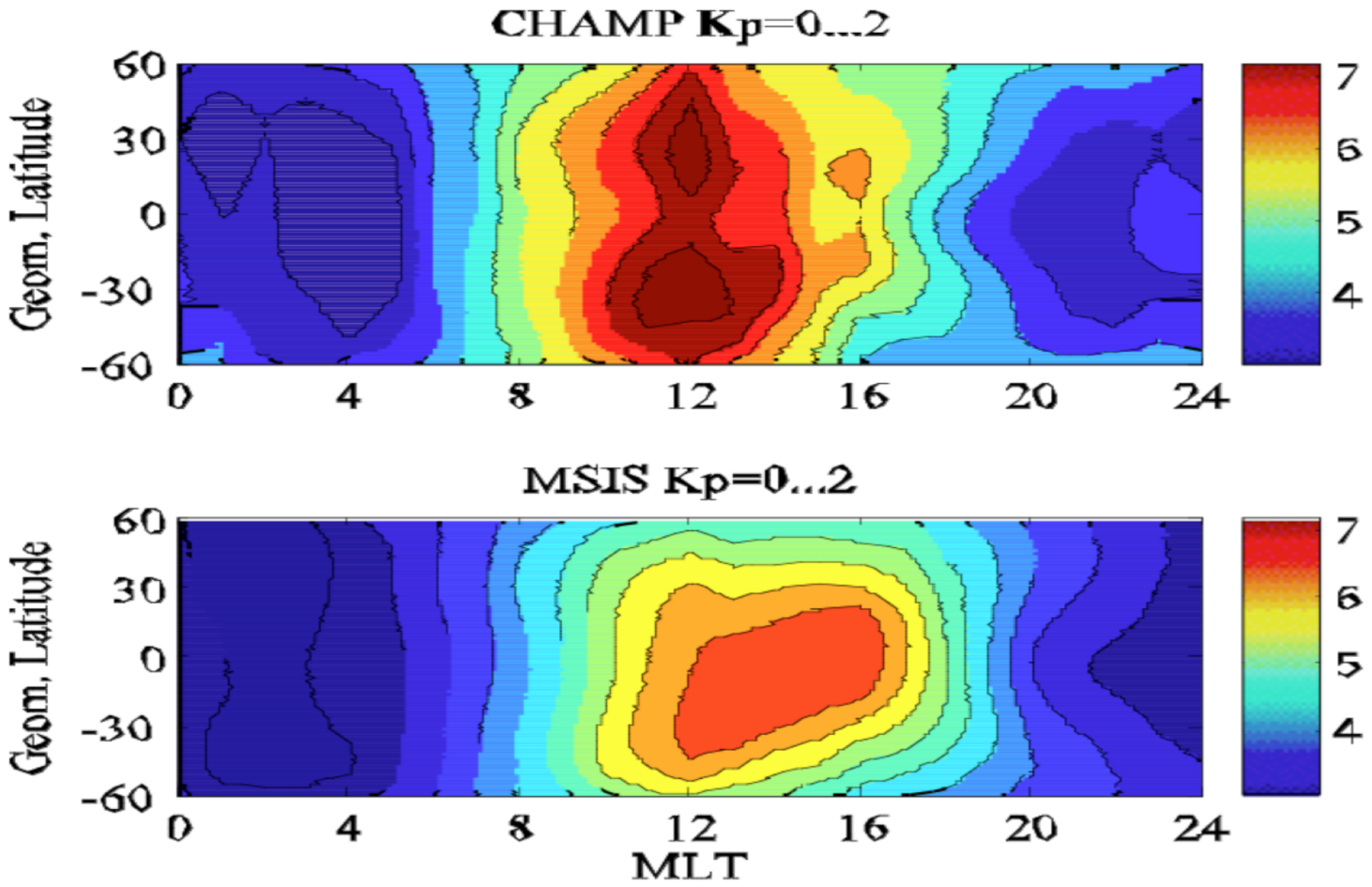
→ **Effects of Forcing from Below**

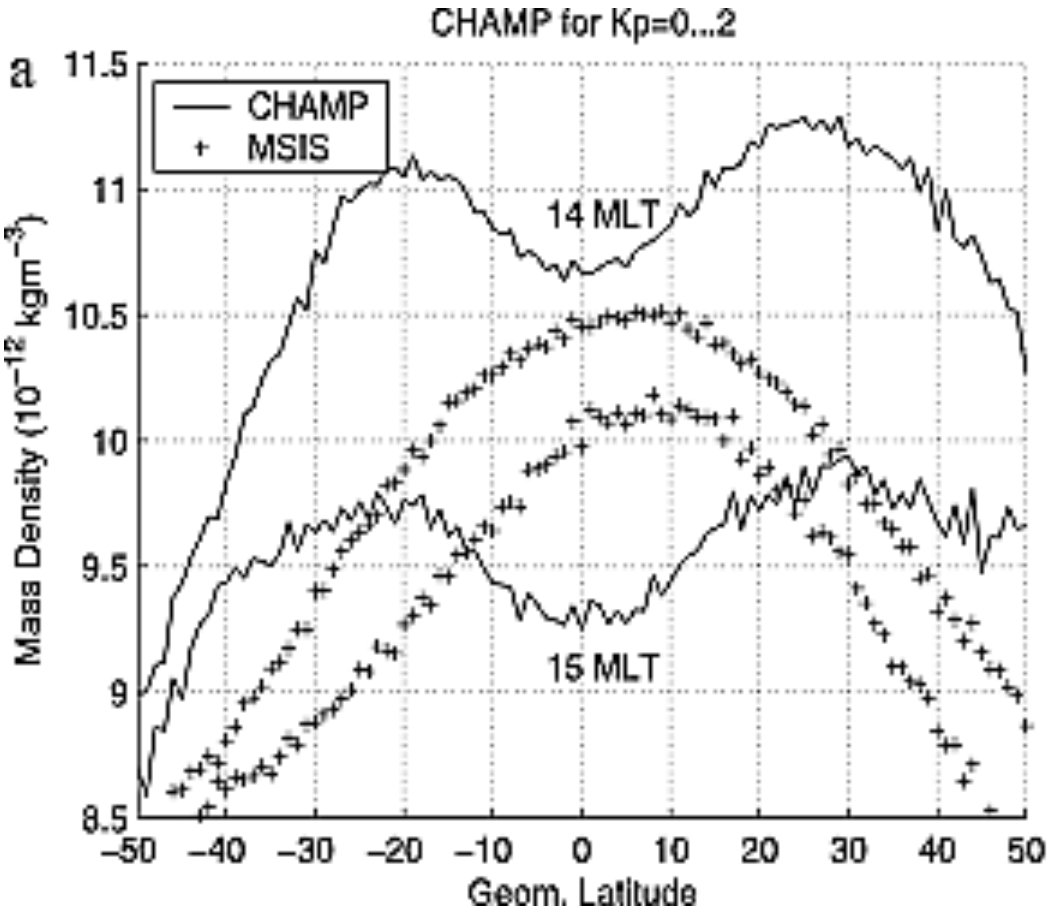
Tidal Forcing Strongly Affects Ionospheric Density as a function of Longitude -- How?



Cosmic-2 data, See Lin et al., 2007

Comparison of neutral density derived from CHAMP accelerometer and models show major differences

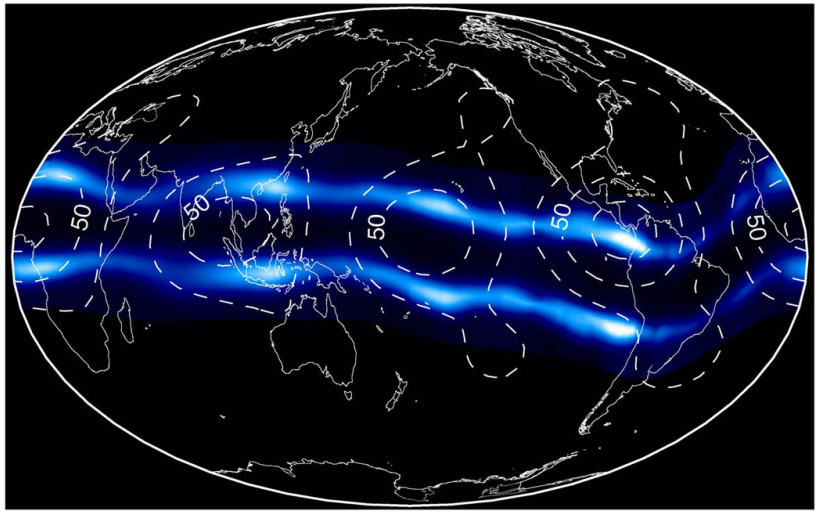




[Luehr et al., 2006]

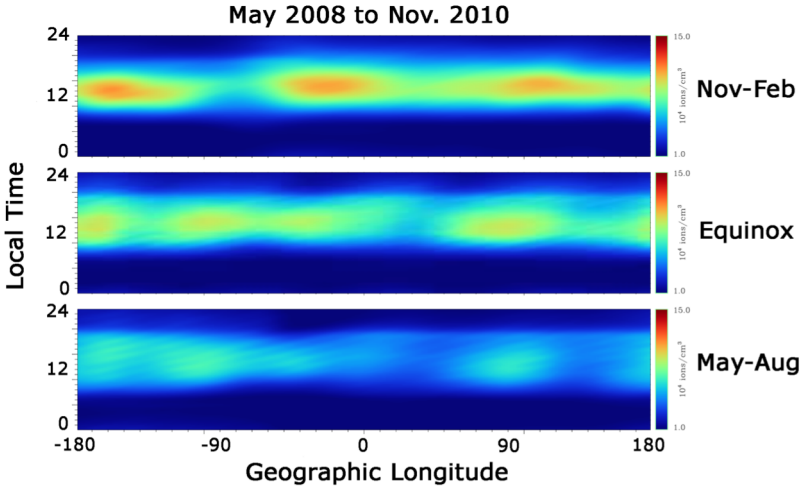
Ionospheric and Thermosphere Response to the Lower Atmosphere

- Numerous observations have shown the IT system responds strongly to forcing from the lower atmosphere
- These forces are structured much differently than those originating in the magnetosphere
  - *Longitudinal structure is prevalent in this form of driving, particularly for tidal modes*
  - *Many important modes do not follow the Sun*
- Therefore IT dynamics at a given point depend strongly on both local time and longitude
- Distinguishing local time effects from longitudinal effects requires multipoint measurements
  - *Currently this distinction can only be accomplished by building statistical pictures*



Tidal effects on plasma density [*Immel et al.*, 2006]

C/NOFS Plasma Density Averages



GD Constellation will address:

How do waves/tides of tropospheric origin contribute to the mean structure, dynamics, and electrodynamics of the thermosphere and ionosphere?

How do neutral winds re-distribute the ionospheric plasma, contribute to global electric fields, and drive instabilities?

What are the changes in planetary waves in the thermosphere during sudden stratospheric warmings? How are these changes related to low-latitude ionospheric perturbations?

Expected Outcome → Major impact to our knowledge of I/T/Mag System and its coupling to the Sun, Space Weather effects

Geospace Dynamics Constellation will provide:

- Breakthroughs in our understanding
- Unprecedented knowledge
- Input for data-starved models
- Address important space weather problems